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Review and recent developments of laser ignition for internal combustion engines applications

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ABSTRACT

Performance of future ignition system for internal combustion engines should be reliable and efficient to enhance and sustain combustion stability, since ignition not only initiates combustion but also influences subsequent combustion. Lean burn systems have been regarded as an advanced combustion approach that could improve thermal efficiency while reducing exhaust gas emissions. However, current engines cannot be operated sufficiently lean due to ignition related problems such as the sluggish flame initiation and propagation along with potential misfiring. A high exhaust gas recirculation engines also has similar potential for emissions improvement, but could also experience similar ignition problems, particularly at idle operation. Similarly, ignition is an important design factor in gas turbine and rocket combustor.

Recently, non-conventional ignition techniques such as laser-induced ignition methods have become an attractive field of research in order to replace the conventional spark ignition systems. The fundamentals of conventional laser-induced spark ignition have been previously reviewed. Therefore, the objective of this article is to review progress on the use of such innovative techniques of laser-induced ignition including laser-induced cavity ignition and laser-induced multi-point ignition. In addition, emphasis is given to recent work to explore the feasibility of this interesting technology for practical applications concerning internal combustion engines.

Contents

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1. Introduction

With increasing restrictions being placed on emissions from modern reciprocating engines as well as increasing demands for higher engine efficiency [1–8], the traditional spark ignition system could face its practical durability limit, as well as its effectiveness cap where igniting ultra-lean fuel/air mixtures is concerned [3]. By shifting to leaner fueling conditions, cooler combustion can be maintained, through which nitric oxides (NO_x) emissions can be dramatically reduced in engines [4–8]. Higher thermal efficiencies can also be achieved due to lower heat loss and higher compression efficiency [6–8]. The increasing of in-cylinder pressure at the time of ignition allows the engine designer to increase the engine efficiency by increasing the power per unit piston area. Such increases in in-cylinder pressure and leaning of the fuel/air mixture are currently limited by the durability of the ignition system and its ability to ignite leaner mixtures at higher pressures.

With conventional spark ignition systems performing well at normal operating conditions, the energy supplied by ignition systems is well above the minimum ignition energy (typically in the order of several tenths of mJ) compared to the order 1–10 mJ of minimum ignition energy required for most hydrocarbons, depending on the mixture strength. However, some future developments in spark ignition engines may require significantly higher spark energies such as those for lean burn high compression ratio engines used for large bore lean burn natural gas fueled engines. Similar ignition energies are required for engines which use alternative fuels such as methane (CH_4), for multi-fuel engines which use a variety of liquid fuels, for low temperature starting of alcohol fueled engines and even for homogeneous charge gasoline engines to enhance early flame growth and improve tolerance to the higher rates of exhaust gas recirculation (EGR) used to reduce NO_x emissions.

However, higher spark energies do not always improve ignitability, but they also decrease spark plug lifetime through increased electrode erosion [9]. Electrode erosion may inherently increases the maintenance cost incurred by users and hence quickly negates any benefits gained. Furthermore, the electrodes act as a thermal energy sink, by taking away a considerable portion of discharge energy thereby reducing the amount of energy that is transferred to the gas for ignition [2]. The development of lean charge associated with fast burn engines requires enhanced ignition devices, through which proper means for increasing the rate of burn of lean mixtures can be obtained. A durable high-energy electrode-less ignition system is therefore a desirable option for overcoming this limitation in higher efficiency ultra lean mixture reciprocating engines [10–12].

For this purpose, various ignition systems have been proposed [9,13,14]; these include high-energy spark plugs, plasma jet igniters, rail plug igniters, laser-induced ignition, flame jet igniters, torch jet igniters, pulsed-jet combustion, and exhaust gas recirculation ignition systems. Many of these systems have features which improve the delivery of ignition energy to the combustible mixture or allow the ignition energy to be dispersed throughout the combustible charge [9]. Among these, laser sources for initiating combustion have many potential advantages and have become an attractive field of research in order to replace the conventional electrical discharge systems [1–8,10–21], despite some limitations that still exist.

Laser-induced spark is a reasonable point energy source in which the amount of energy, the rate of its deposition and ignition timing can be controlled precisely. It also permits the choice of optimal ignition location, which is not easy in conventional ignition systems. In addition, the absence of a material surface in the vicinity of the ignition location minimizes the effect of heat loss during flame kernel development and hence, the lifetime of a laser ignition system is expected to be significantly longer than that of conventional spark ignition systems [21]. Furthermore, for equivalent amounts of system input energy delivered to the spark, the laser ignition system provides a much larger initiating spark volume as compared to an electrical spark [2]. Moreover, laser ignition is capable of providing multi-point ignition sites [19,20,22–24], that can be controlled to ignite a gaseous combustible mixture either sequentially or simultaneously rather comfortably as compared to conventional electric ignition systems using spark plugs. These characteristics not only provide valuable research areas but also, if the overall size of laser units can be reduced sufficiently, potentially improve practical igniters, albeit requiring suitable windows for laser beam access.

Recently, the conventional techniques and fundamentals of laser-induced ignition have been reviewed extensively [9,25,26]. Therefore, the objective of this paper is primarily to examine and review developments with the innovative techniques of laser-induced ignition and to identify promising systems which might aid in the development of future combustion related applications. In this regard, only a brief review of laser-induced ignition fundamentals is included while more detailed comments on the present developments of new laser-induced ignition techniques including laser-induced cavity ignition and laser-induced multi-point ignition is presented. In addition, recent work concerning applications of laser-induced ignition to practical engines is covered.

2. Fundamentals of laser-induced ignition

Laser-induced ignition has been tested and/or used for a wide variety of applications in many practical combustion devices including, ignition of gaseous fuels in internal combustion engines [2,5–8, 27,28]; ignition of high explosives [29,30]; ordnance [31–33] and rocket motors [34,35]; ignition of liquid fuel sprays [36–39] as used in turbines [40,41] and jet engines [42]; flameholders and stabilizers for supersonic combustion applications [43].

Fundamentally, there are four different mechanisms by which laser light can interact with a combustible mixture to initiate an ignition event. They are referred to as thermal initiation, photochemical ignition, resonant breakdown, and non-resonant breakdown [25,26]. The relative importance of each mechanism depends on the wavelength of the laser beam used.

2.1. Thermal initiation

Thermal ignition is initiated when low energy long wavelength laser radiation is incident on a target material that is a strong absorber, solid or gaseous, in a gaseous combustible mixture [2]. Thermal initiation utilizes infrared (IR) laser energy to vibrationally and/or rotationally excite a specific highly absorbing species within the combustible mixture to induce ignition. Ignition takes place when the target absorber transfers sufficient energy to the combustible mixture to cause autoignition.

Although laser equipment are readily available to such a thermal ignition system, they are rather impractical due to their requiring a portions of the system to be sacrificial, similar to erosion in spark plug electrodes, whether it is a fuel additive or a part of the engine. Moreover, as reported by Ronney [25] and Phuoc [26], breakdown-type sources are probably ruled out for line-source ignition studies because of the focusing required to obtain breakdown.

2.2. Photochemical ignition

Photochemical ignition occurs when a high energy photon dissociates a molecule allowing the ionized constituents to react with the surrounding gases [2]. This type of ignition mechanism is similar in concept to the thermal ignition regime; however the

primary difference is the photon energy of the incident radiation and the fact that the absorber is the gas to be ionized and not a secondary solid or gas. Thermal initiation utilizes IR laser energy to vibrationally and/or rotationally excite specific noncombustible yet highly absorbing species within the combustible material to induce combustion. The photochemical process employs ionizing radiation in the ultraviolet (UV) wavelength range or higher. Neither the IR nor visible photons contain sufficient energy to photo ionize most molecules and require multiple photons to ionize the combustible gas molecules.

This high energy radiation is denoted ionizing because a single photon contains sufficient energy to overcome the ionization potential of certain molecular species and can directly initiate a sustainable chemical reaction. It has been reported that due to high reactive radical production rates, the minimum laser ignition energy for certain mixtures is shown to be below one millijoule [44–46].

This is an attractive method for initiating combustion because, in comparison with other ignition mechanisms, photochemical ignition can be used to ignite mixtures at lower pressure and closer to the flammability limits, as long as a sufficient amount of reactive radicals can be generated from the target molecules [26]. However, as pointed out [26], there are many disadvantages in adopting photochemical ignition in practical applications. Photochemical ignition requires a close match between the laser excitation wavelength and the target molecule's absorption wavelength in order for dissociation to occur. A particular or tunable laser, therefore, might be required to provide such a match. Since the photon energy at visible and near-IR wavelengths is smaller than the dissociation energy of most gases, the photochemical ignition process is most effective at UV wavelengths. At present, the equipment needed for such a system are extremely cost prohibitive and lightweight lasers for practical combustion applications are not readily available.

2.3. Resonant breakdown

Resonant laser ignition is initiated by the dissociation of target molecules or atoms by the non-resonant multiphoton ionization process, as first reported by Forch and Miziolek [47,48] and by Forch [49]. The dissociated atoms or molecules are then resonantly ionized via multiphoton ionization by continued laser illumination [47–49]. The electrons generated by the resonant ionization gain energy via the inverse Bremsstrahlung photon absorption process can induce breakdown via the electron cascade process.

A limited number of experimental studies have been published concerning resonant laser ignition. The studies published to date have indicated the feasibility of this technique and the distinct advantage of greatly reducing the required ignition energy when the proper laser wavelength is applied to a specific gas mixture due to a larger portion of the laser pulse energy being used to heat up the plasma.

The resonant laser ignition technique can be very attractive and extremely efficient when compared to non-resonant breakdown since a larger portion of the laser pulse energy being used to heat up the plasma [26]. However, the construction and operation of laser systems that produce the needed output wavelength are difficult and expensive at present.

2.4. Non-resonant breakdown

Non-resonant breakdown occurs when a laser pulse of sufficient peak power is focused to a sufficiently small spot whereby the electrical field component of the focused light is strong enough to influence the gas molecules and initiate the electrical breakdown of the gas [25]. There are two different mechanisms that dominate the initiation of the breakdown process depending on the characteristics of the laser energy and the gaseous medium. They are referred to as multiphoton ionization and electron cascade ionization [50,51].

Multiphoton ionization involves the simultaneous absorption of a sufficient number of photons by a gas molecule or atom to cause ionization [51]. The absorption of photons induces the ejection of a valence electron into the conduction band where the electron is considered free of the atomic or molecular system and gains energy from the time varying electromagnetic fields produced by the focused laser radiation [51]. The free electrons also absorb kinetic energy from the incident radiation via the inverse Bremsstrahlung process and are then able to ionize the molecules or atoms within the focal volume producing an even greater number of free electrons [50,52]. The free electrons grow exponentially in number until the local electric field potential exceeds the breakdown potential of the gas. Once the local breakdown potential is exceeded, a plasma discharge ensues which can produce localized temperatures of approximately 10^6 K and localized pressures of approximately 10^3 kPa [50,52]. For very short pulse duration (few picoseconds) the multiphoton processes alone must provide breakdown, since there is insufficient time for electron-molecule collision to occur [25].

The most dominant plasma producing process, as pointed out by Weinrotter et al. [21], is the electron cascade ionization process by which initial electrons absorb photons out of the laser beam via the inverse Bremsstrahlung process. If the electrons gain sufficient energy, they can ionize other gas molecules on impact, leading to an electron cascade and breakdown of the gas in the focal region. It is important to note that the electron cascade process is dependent on two necessary conditions. The first condition requires that initial electrons must be within the focal volume irradiated by the laser energy to initiate the process [51]. The second condition requires that the electrons must acquire an energy level greater than the ionization energy of the gas for the cascade to take place [51]. The initial electrons are produced from impurities in the gas mixture (dust-, aerosols- and soot-particles) which absorb the laser radiation and lead to high local temperature and in consequence to free electrons starting the avalanche process. In contrast to multiphoton ionization, no wavelength dependence is expected for this initiation effect [53]. It is also very unlikely that the first free electrons are produced by multiphoton ionization since the power intensities in the focus regions (10^{10} W/mm^2) are too low to ionize gas molecules via this process, which requires intensities of more than 10^{12} W/mm^2 [54].

3. Laser-induced spark ignition

3.1. Characteristics of initial flame kernel

By far, non-resonant breakdown is the most frequently adopted ignition mode to initiate combustion primarily because of its freedom in selecting the laser wavelength needed and the ease of implementation and is generally termed laser-induced spark ignition.

Photographs of laser-induced sparks [10,14,55–60] showed that they were asymmetric in the direction of the laser beam such that two distinct segments were observed during the initial flame kernel development: a *torus-like shape* propagating radially and a *third lobe* propagating back toward the laser source, as exhibited in Fig. 1 [55]. Fig. 1 shows an OH-PLIF series of laser ignition of a CH_4/air mixture ($\phi = 0.9$) [55]. Here, the tendency of the flame to move back towards the laser source forming a third lobe is evident.

Although observed by several researchers, the third lobe has not been fully explained. Spiglanin et al. [59] suggested that the

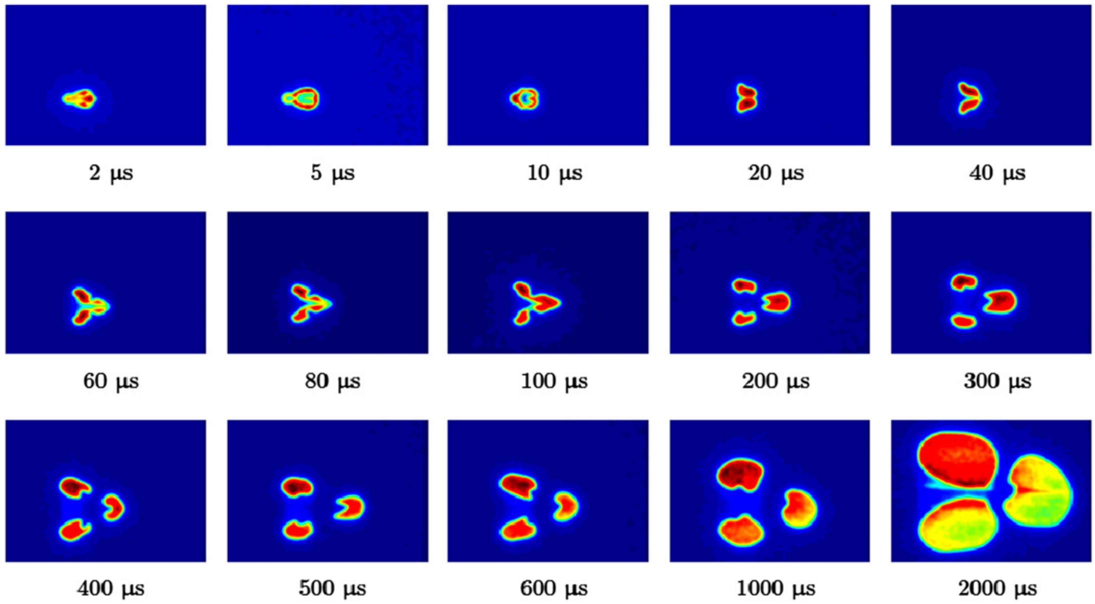

Fig. 1. OH-PLIF series of laser ignition of a CH_4/air mixture of $\phi=0.9$ [54].

evolution of the third lobe could be due to the initial flow field created by the propagation of a radiation transport wave up the laser beam, arising from the high rate of energy transfer at the leading edge of the plasma. Certainly, the plasma kernel created by laser breakdown can result in an ionized front propagating toward the laser, with some movement "upstream" from the focal point. However, this would not be expected to continue long after the laser pulse had ceased and, as already pointed out, there is no evidence of this. Another, gas dynamic explanation [59] attributes the third lobe to either the possibility of the ionized gas facing the incoming laser beam to absorb more laser energy, and thus the boundary of a highly heated plasma could propagate back toward the laser source, or to the propagation of a shock wave generated from the initial expansion of flame kernel with an axial component toward the laser source [59].

Ready [58] has referred this formation to the acceleration of plasma produced by the nonlinear interaction of light with inhomogeneous plasma as a result of the phase difference between current density and magnetic flux when entering the plasma. Several other mechanisms have also been suggested, including a breakdown wave, a radiation transport wave, and a traveling ionization wave [26].

3.2. Initial flame kernel modeling

The characteristics of the laser-induced spark have been modeled [61] including hydrodynamic expansion, electron thermal conduction, the Coulomb interaction between electrons and ions, free–free absorption of incident laser radiation, and inverse Bremsstrahlung radiation. A very small spark was assumed to exist at the focus, and the subsequent shock wave was described as a spherically symmetric Chapman–Jouguet detonation wave during the laser pulse and as the Taylor blast wave after the laser pulse. It has also been modeled as a simple Taylor blast-wave process assuming a spherical shock-wave propagation [59,62].

Although there have been many suggestions on the formation of the third lobe in the laser-induced spark kernel, including the asymmetric absorption of laser power in the direction of laser, it has not been clearly substantiated in modeling efforts, especially for combustible mixtures. Motivated by this, Morsy and Chung [15] proposed a hydrodynamic model for predicting the formation of a third lobe by depositing asymmetric laser energy, through which the formation of a third lobe has been successfully predicted.

In their study [15], numerical simulations for the development of flame kernel by laser-induced sparks have been performed during the early stage of flame propagation. Pressure, temperature, and associated flow fields have been evaluated by solving the relevant conservation equations using the KIVA-II code [63]. Laser energy absorbed by a spark has been modeled here considering temporal and spatial distribution. Especially, asymmetric absorption in the direction of laser beam has been taken into account. It was assumed that, as initial conditions, a cylindrical breakdown region of 0.4 mm radius and 1.5 mm length was formed for the mixture of equivalence ratio of $\phi=0.7$ with a peak temperature of 10,000 K and a peak pressure of 10 atm in the pre-assumed breakdown region and a spark energy of 25 mJ was assumed to be absorbed during the laser-pulse duration. Outside the breakdown region, the initial temperature and pressure were taken to be $T_i=300$ K and $P_i=1.0$ atm, respectively, while energy losses by light scattering and radiation were neglected. Initial flow velocity was taken to be zero everywhere. A spatial distribution of laser-energy deposition is of particular importance. This has been fitted to an axisymmetric Gaussian distribution [64] in a direction normal to the laser beam. In the laser-beam direction, the location of peak intensity is shifted toward the laser source from the focal point [52,64], which has been substantiated from the planar laser-induced fluorescence images of OH [59]. A detailed discussion concerning the spatial intensity of laser beam and chemistry used in simulation process can be found elsewhere [15].

The velocity fields and corresponding temperature profiles of the initial stages of flame kernel formation for a lean mixture of CH_4/air are shown in Fig. 2. It can be seen that a torus-like shape flame kernel propagated radially and a front lobe was formed, which propagated back toward the laser source. These kernel structures were developed due to vortical motions generated by the interaction of the pressure field and flow, which stem from the asymmetric deposition of laser energy in the direction of laser. The front lobe was separated from the flame kernel for the lean mixture, as can be seen from Fig. 3, but it was found to be extinguished for the same mixture at sub-atmospheric conditions. Nevertheless, it was found that the calculated results of the flame

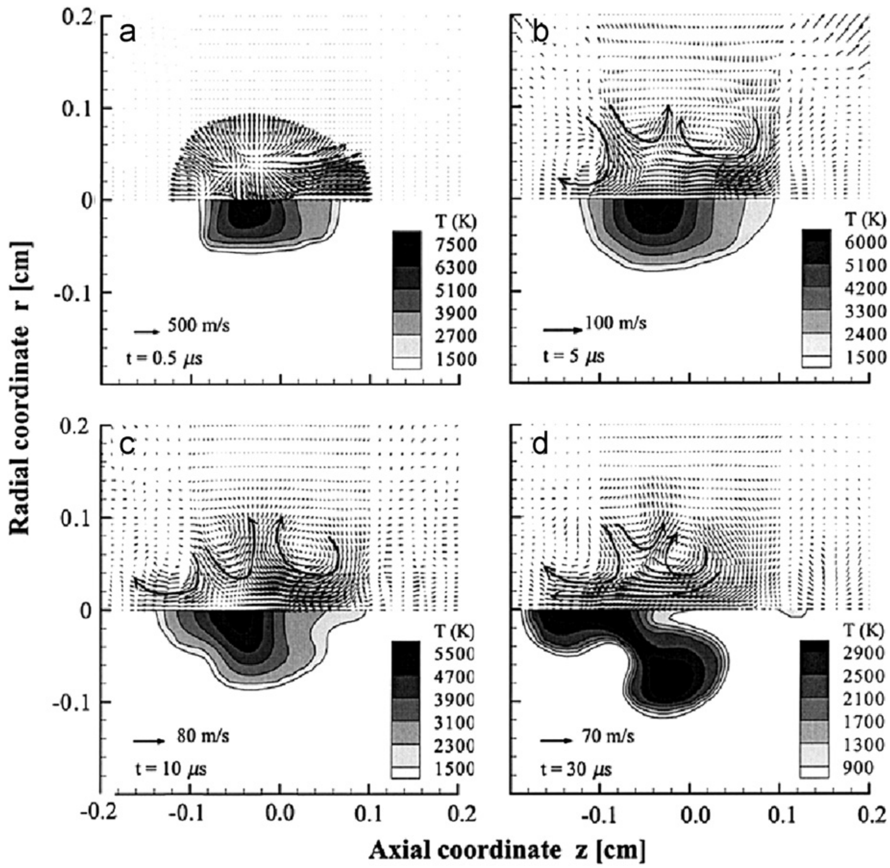

Fig. 2. Velocity fields (top) and temperature profiles (bottom) for CH_4/air mixture with ϕ=0.7 and P_i=1.0 atm: (a) t=0.5 μs, (b) 5 μs, (c) 10 μs, and (d) 30 μs [15].

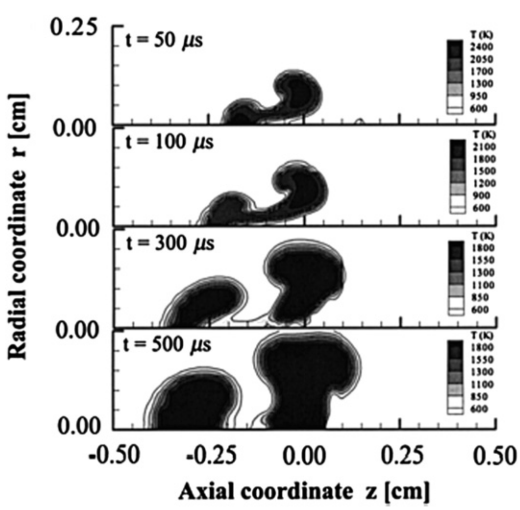

Fig. 3. Temperature profiles after laser shot for CH_4/air mixture with ϕ=0.7 and P_i=1.0 atm [15].

kernel and subsequent flame propagation agreed well with experiment concerning the formation of the third lobe and the effects of the pressure and equivalence ratio [15]. It is worth noting that the similarity between the experimental results (Fig. 1) and numerical simulations (Figs. 2 and 3) is very clear. These results showed the importance of considering the hydrodynamic effects resulting from the asymmetric absorption of laser power on the formation of front lobe and torus-like shape flame kernel through the development of vortical structures [15]. The formation of third lobe could increase the burning rate and hence reduce the combustion time [24–26]. Since the numerical calculations were based on the asymmetric energy deposition in the axial direction with the peak intensity displaced toward a laser source, the numerical results support the explanation of the formation of the third lobe in that the ionized gas facing the incoming laser beam could absorb more incident energy [58].

Phouc [65] studied the expansion and energy balance of the laser-induced spark in air. In his study, the numerical analysis used a simple one-dimensional spherical model and the governing equations were integrated numerically using the MacCormack predictor–corrector scheme (a widely used discretization scheme for the numerical solution of hyperbolic partial differential equations). It was assumed that (i) the expansion was spherical one dimensional, (ii) body forces were neglected, (iii) conditions for local thermodynamic equilibrium were valid, (iv) the magnetic field generated by the electrical current passing through the plasma was negligible, and (v) all constituents of the plasma behave identically as far as their thermo-mechanical response is concerned. It was found that the shock radius, R, is proportional to the shock arrival time $t^{0.4}$ and the shock pressure is proportional to R^{-3} as functionally described by the blast wave theory [65]. For the range of the spark energies from 15 to 50 mJ, the shock front reached a distance of approximately 2 mm within a few microseconds or less. During this period the shock-wave energy loss was approximately from 51% to 70% while the radiation energy losses accounted for were from 22% to 34%, and the energy of the remaining hot gas being approximately 7–8% of the absorbed energy.

Bradley et al. [57] discussed the effects of turbulence and pressure on the limits of flammability. In their study, it was found that the lean ignition limit for iso-octane/air mixtures at 358 K increases as the turbulence level increases and decreases as the pressure increases. With zero or small turbulence levels, the lean ignition limit was not only greater than the lower flammability

limit but also greater than that observed with conventional electric spark ignition systems. This was in agreement with the finding by Phuoc and White [10] who found that at a 1064 nm Nd:YAG laser failed to ignite a methane–air mixtures at a value of ϕ near and above the lean flammability limit. Similar to a numerical study reported by Morsy and Chung [15] and Spiglanin et al. [59], they also observed that, when the spark is created, a rarefaction wave created two contra-rotating toroidal rings at the leading and trailing edges of the plasma. The former decayed more rapidly and a third lobe of the kernel was generated and moved towards the laser.

The plasma generated by laser ignition in air has been also modeled using blast wave theory and quasi equilibrium thermodynamic computations [66,67]. The computational approach was also used to assess the effect of 1%-hydrogen addition to the dry air [67]. The modeled results were generally in good agreement with the experiments for pressures from ambient pressure [66,67] up to 6.9 bar [67], suggesting the validity of their experiment. However, at higher pressures (20.7 bar and above) and higher plasma temperatures, the measured and modeled results do not agree very well. This discrepancy might be due to the overestimation of the energy absorbed by the plasma at high pressures as well to the possible effects of spatial inhomogeneity within the plasma. Also, it was found that the addition of 1% hydrogen did not result in any significant change in the thermochemical plasma properties [67].

4. Laser-induced cavity ignition

Although depending on devices, one of the main disadvantages of laser-induced spark ignition was that energy conversion efficiency of a laser system is still not high enough and only a portion of the laser energy is absorbed by the gaseous medium in the vicinity of the ignition location [18,25,68]. Here, it was found that only 30–70% of the incident laser energy can be utilized in laser-induced spark ignition [18] with the rest of the laser energy being lost due to the unabsorbed laser beam passing through the ignition location and being then scattered at the wall of a combustion chamber, so that it cannot be utilized in the ignition process. However, recent and future advances of laser systems would hopefully result in high power-conversion rate systems within a very compact size in the near future.

Motivated by this, Morsy et al. [18] proposed an alternative method of laser-induced ignition in which the principle of a beam stop (dump) was applied to confine almost the entire incident laser energy inside a conical cavity. The working principle of this method is shown in Fig. 4, where a non-focused laser beam is directed into the conical cavity with part of the incident laser energy being absorbed at the surface of a cavity while the rest of the energy is reflected inside it. The reflected laser beam is directed toward the apex of the cavity and multiple reflections at the cavity surface effectively confined almost all the incident energy within it through a focusing effect along the central axis of the cavity, as illustrated in Fig. 6. If the laser intensity along the axis of the cavity is large enough, breakdown will occur and a laser spark will be generated [18]. In their experiment [18], two conical cavities (cavity I and cavity II) of different diameter and depth were tested. The smaller cavity II utilized less laser energy (40–55 mJ) for ignition than the larger cavity I (80–110 mJ) depending on the mixture strength.

Shadowgraphs, as demonstrated in Figs. 5 and 6, of the early stages of the combustion process for quiescent methane/air mixtures show that a hot gas jet was ejected from the cavity a few milliseconds after the laser was fired. This jet could have a similar effect to that in plasma jet ignition. Since plasma jet

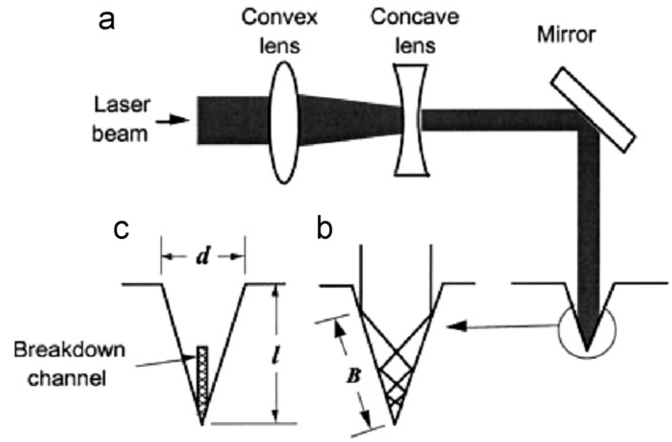

Fig. 4. Diagram showing laser-induced ignition using a conical cavity: (a) optical arrangement, (b) principle of multiple reflection inside cavity, and (c) model of breakdown channel for numerical calculation [18].

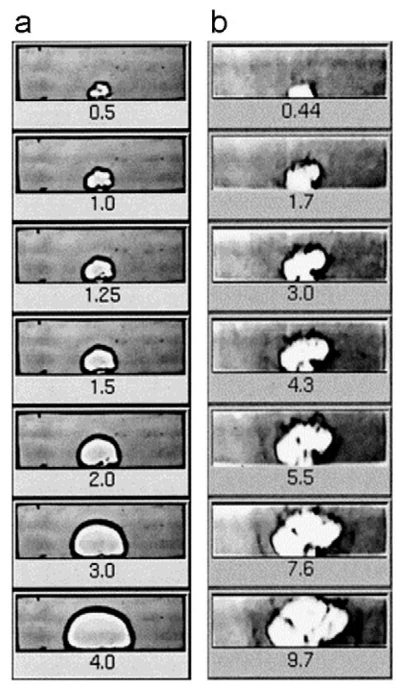

Fig. 5. Shadowgraphs for early stages of combustion process using cavity I for CH_4/air mixtures with P_i=1.5 atm, (a) ϕ=1.0, and (b) ϕ=0.7 (numbers indicate time [ms] after laser shot) [18].

ignition requires very high energy levels (of the order of several joules) [9], while the energy needed for the laser-induced cavity ignition can be much lower, the corresponding jet intensity can therefore be weaker. During subsequent flame propagation, both similarities with and differences from conventional spark ignition processes were observed, depending on the cavity size and the concentration of mixtures. Similar results have been obtained by Ryu et al. [23]. With laser cavity ignition, it was also found that the combustion pressure increased relatively rapidly and a higher maximum pressure could be achieved. As a result, the combustion duration for laser cavity ignition was decreased relative to the conventional laser-induced spark ignition [18].

Their results [18] suggested that the problem of lower laser energy absorption by gaseous medium could be circumvented by using laser-induced cavity ignition that utilizes almost the entire laser energy for ignition, although some of the advantages mentioned previously for laser-induced spark ignition are thereby

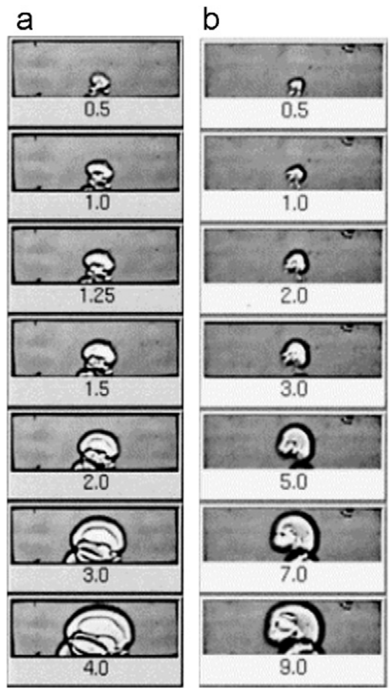

Fig. 6. Shadowgraphs for early stages of combustion process using cavity II for CH_4/air mixtures with P_i=1.5 atm, (a) ϕ=1.0, and (b) ϕ=0.7 (numbers indicate time [ms] after laser shot) [18].

sacrificed with this approach. In addition, as will be discussed later, the idea of a laser-induced multi-point ignition is mainly based on using either a cavity on one side (two point ignition) or two cavities on both sides (two and three point ignition) of the combustion chamber [19,20,23], which could be assumed as the main benefit of laser-induced cavity ignition.

Flame kernel development and the subsequent combustion process for laser-induced cavity ignition have been also investigated numerically by Morsy et al. [18] using the KIVA-II code [63] for stoichiometric methane/air mixture. Adopting the same procedure used in simulating the laser-induced spark ignition [15] discussed earlier, an initial high-temperature region around the focal point was assigned. It was assumed that at time t=0, a cylindrical breakdown channel of radius 0.08 mm is formed on the axis of the cavity with a peak temperature of 10,000 K and a pressure of 8 atm. The length of the cylindrical breakdown channel was determined by the laser beam diameter and the geometry of the cavity, as illustrated in Fig. 4(c). Outside this channel, the initial temperature and pressure of the mixture were taken to be T_i=300 K and P_i=1.5 atm, respectively. No slip condition was applied at the solid boundaries. Heat transfer from the flame kernel to the wall of the cavity was considered while the energy losses due to radiation were neglected. The initial flow velocity was taken to be zero everywhere inside the combustion chamber.

For the simulation of laser-induced ignition with a conical cavity, an energy source term was introduced into the energy conservation equation and a Gaussian-like profile was assumed. It was assumed that the inside wall of the cavity, corresponding to region B in Fig. 4(b), absorbs a fraction of the incident laser energy which heats up the surface without any phase change due to both the wavelength and the pulse duration of the laser beam being short. The initial temperature of the chamber wall was taken to be 300 K. The instantaneous surface temperature, T_s, heated by a Gaussian laser beam, chemistry used and simulation procedure can be found in details elsewhere [18].

Numerical results showed that a series of vortices inside and outside the cavity were developed and cold gas entrained into the cavity. As a result, hot gas in the cavity was ejected out along the cavity wall. The reduction in reaction time associated with cavity ignition was attributed to the series of vortices promoted by the ejection of hot gases from the cavity into the surrounding environment. Fig. 7 shows the calculated results for the spatial distribution of temperature at four selected time steps during the combustion process. It can be seen that the calculated flame propagation, illustrated by the temperature distribution, agreed well with the combustion process observed from the shadowgraphs presented in Fig. 5(a).

5. Laser-induced multi-point ignition

In order to reduce the NO_x emissions of a gas engines, the air–fuel mixture is diluted to reduce the peak temperature inside the cylinder during combustion, since NO_x emissions are mainly affected by combustion temperatures and the availability of oxygen. As a consequence, the speed of the expanding flame front decreases to unacceptable values for very lean mixtures [26], and thus significantly diminishing the efficiency of the engine. For large bore engines, because the flame propagation distance is long, the above problems become more serious. Therefore, gas engines, especially of large bore, are sometimes equipped with two or more spark plugs to avoid these serious problems and to increase their lean-operation performance, besides employing turbulence.

Multi-point ignition becomes necessary to compensate the loss in flame speed. With multi-point ignition, the distance over which the flame must sweep to complete the combustion process is shortened. Because the combustion times are short, the flame does not have enough time to lose heat resulting in higher combustion temperatures and pressure leading to a better thermal efficiency and increased power output.

Furthermore, all practical combustion engines employ turbulence to accelerate mixing and/or burning; however, this turbulence also increases heat losses to the walls and pressure drops. In a typical automotive engine, the heat loss to the cylinder walls comprises 20–30% of the fuel energy input [25]. Hence, if the need for acceleration of combustion by turbulence could be reduced by employing multiple-point laser ignition, it is possible to redesign the combustion chamber to obtain lower turbulence levels, and thus lower heat losses.

Laser ignition is capable of providing multi-point ignition sites that can be controlled to ignite a gaseous combustible mixture either sequentially or simultaneously rather comfortably as compared to conventional electric ignition systems using spark plugs. It has been reported that multi-point ignition could enable one to avoid problems such as early flame quenching, partial burn, misfire, pressure pulsation and cycle-to-cycle variation associated with combustion of lean mixtures [25,26].

Multi-point ignition techniques with a single-shot laser have been proposed and their feasibility has been tested experimentally in a constant volume chamber filled with either premixed CH_4/air mixture [19,22,23] or H_2/air mixture [20,27]. Two-point ignition has been achieved with a single-shot laser in which laser-induced *spark* ignition was followed by laser-induced *cavity* ignition [19]. The working principle of this technique is schematically shown in Fig. 8(a) in which the laser beam is focused at the desired location to effect *spark* ignition, and the unabsorbed beam is directed into the conical cavity for *cavity* ignition.

Shadowgraphs of such two-point ignition setups are shown in Fig. 9 for CH_4/air mixtures of ϕ=1.0 and 0.7 where P_i indicates the initial chamber pressure. Respective flame front development is similar to that from a single-point laser-induced spark [55] and

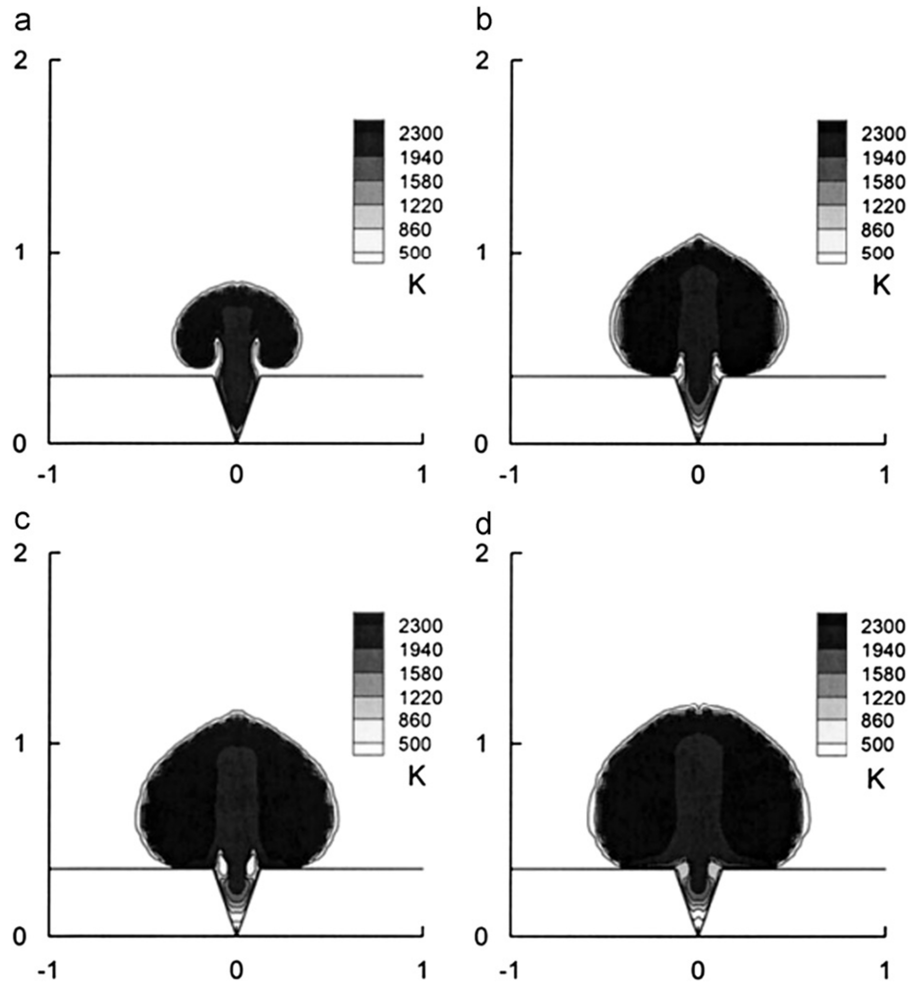

Fig. 7. Temperature field for stoichiometric CH_4/air mixture for $P_i = 1.5$ atm; (a) $t = 0.5$ ms, (b) 1.0 ms, (c) 1.25 ms, and (d) 1.5 ms [18].

cavity [18] ignitions. In comparison with single-spark or single-cavity ignition, it is found that the reduction in the flame initiation period (e.g., time to reach 5% of maximum pressure) by the two-point spark/cavity ignition was approximately 45–69% and it became more pronounced at lower initial combustion chamber pressures. This reduction in the flame initiation period could mitigate the problems of cycle-to-cycle variation in engines, frequently associated with lean-combustion. The total combustion time (time to reach 90% of maximum pressure) for the two-point ignition case was also reduced by approximately 28–45% depending on the initial pressure.

Similar results were also observed by Phuoc [22] who studied the effects of multi-point versus single-point ignition on combustion pressure and combustion time for CH_4/air, CH_4/O_2, H_2/air, and H_2/O_2 mixtures. In his work, different methods were used to achieve two-point ignition in which two laser beams were delivered and focused into the ignition cell from opposite directions using two identical beam delivery optical systems. The total laser energy used in his study was the same for both single-point and two-point ignition. Thus, the observed reduction in combustion times was strictly due to the effect of multi-point ignition.

Fig. 10 shows a series of images of the ignition and combustion process of a stoichiometric mixture of CH_4/air at atmospheric pressure ignited by a laser spark of energy of approximately 7.5 mJ. It is clear that two-point ignition started with two identical flames propagating toward the wall and toward each other. The flame fronts that were propagating toward each other stretched vertically as they approached each other. In comparison with the other two ignition configurations, the whole process was very much shorter. The time required for complete combustion was approximately 50% shorter than that required for the wall-ignition case, and approximately 75% shorter compared to the time required for the center-ignition case. It was also found that the peak pressure for two-point ignition is always between 79 and 118 kPa higher than a single ignition point and the time necessary for complete combustion of the mixture is drastically reduced when two-point ignition is used.

Morsy and Chung [20] expanded their work and proposed a new method of laser-induced multi-point ignition with H_2/air mixture ($\phi = 0.3$) by utilizing two conical cavity arrangement, one of which has an opening at its apex region as shown in Fig. 8(b) and (c). By directing unfocused laser beam into the first cavity, part of the incident laser energy passes through the opening and irradiates into the second cavity as shown in Fig. 8(b). Simultaneous two-point ignition was achieved at each cavity. A simultaneous three-point ignition technique was based on directing a focused laser beam into the two-cavity arrangement, which produces additional ignition at the center of the chamber through laser-induced spark ignition as shown in Fig. 8(c) [20].

One of the advantages of this laser-induced multi-point ignition method is demonstrated in a series of shadowgraphs for the early stage of the combustion process shown in Fig. 11 [20]. The ejecting hot gaseous jet from the second cavity and subsequent flame development exhibited similar behavior as to the one with the single-point laser-induced cavity ignition [18]. However, the jet from the first cavity, which was connected to a small prechamber, exhibited an appreciable delay compared to the jet

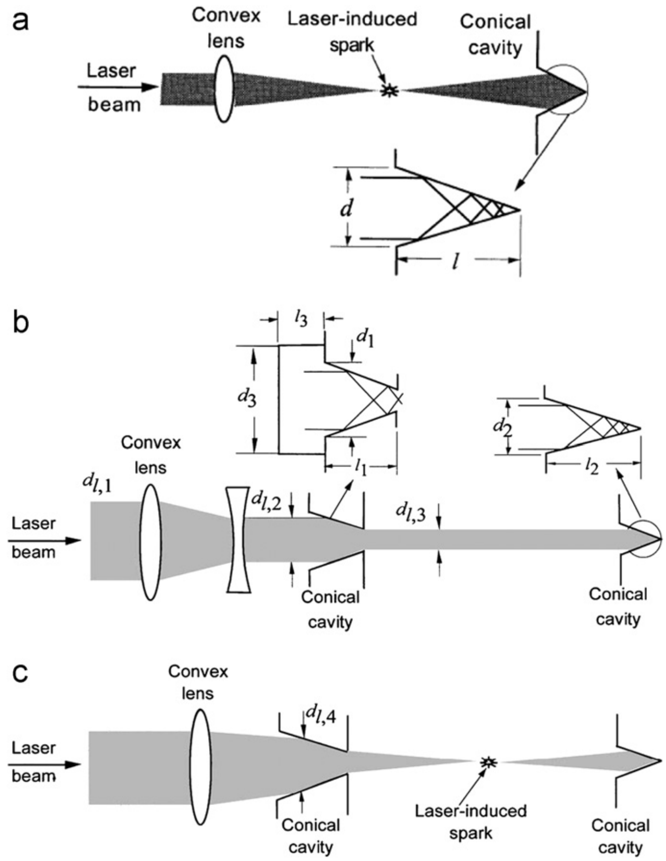

Fig. 8. Principles of laser-induced multi-point ignition showing multiple reflection characteristics inside cavities. (a) two point spark/cavity ignition [19], (b) two point cavity ignition and (c) three point ignition [20].

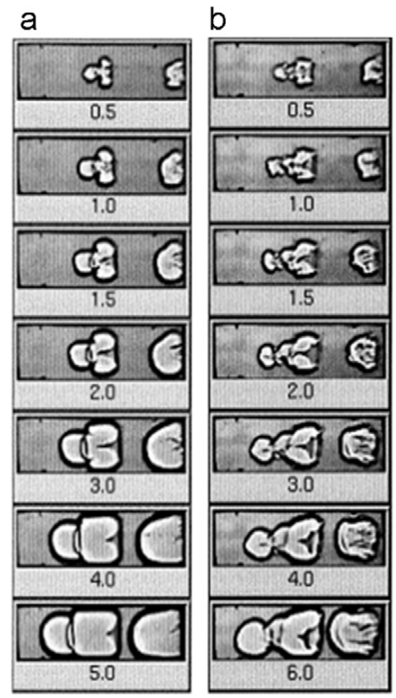

Fig. 9. Shadowgraphs for early stages of combustion processes of CH_4/air mixtures with two-point ignition; (a) P_i=1.5 atm, ϕ=1.0, E_0=80 mJ, and (b) P_i=1.0 atm, ϕ=0.7, E_0=110 mJ (numbers indicate time [ms] after laser shot) [19].

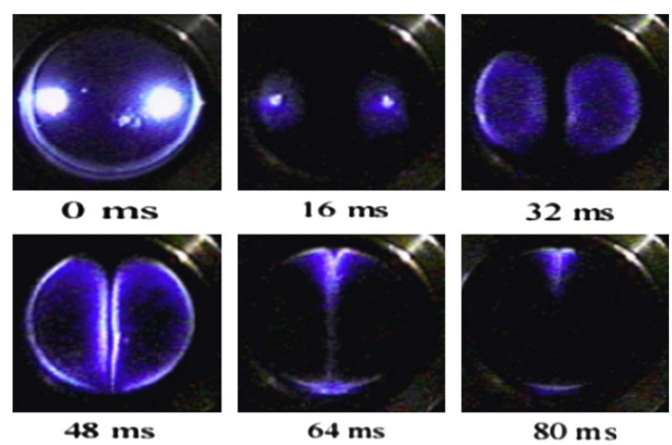

Fig. 10. Typical images of two-point ignition for a stoichiometric CH_4/air mixture [22].

issuing from the second cavity. This can be attributed to the existence of the additional volume of the prechamber. It was expected that the flame kernel initially grew into the prechamber prior to the jet ejection into the main chamber. The prechamber has a desirable effect on the penetration speed of the jet, that is, the jet from the first cavity penetrates faster after certain induction time compared to that from the second cavity. As a result, the two flame fronts merge nearly at the center of the main chamber. For the three-point ignition case (Fig. 11(b)), the flame front behavior can be better understood by combining the behavior of the laser-induced two-point ignition system with two cavities (Fig. 11(a)) and of the laser-induced spark ignition. Both the flame initiation period and the total combustion time have been significantly decreased with multi-point ignition [20]. The multiple ignition locations have an additional advantage of shortening the distance for the flames to travel, enabling a significant reduction in combustion time. Thus, the use of multiple-point ignition can appreciably improve the performance of an engine.

Similar results were also observed by Ryu et al. [23] who were able to achieve up to five ignition sites simultaneously with a single-shot unfocused laser beam by installing an extra two holes into a small prechamber connected to the main chamber, as schematically shown in Fig. 12. In their experiments, four cases of laser-induced multi-point ignition have been tested as summarized in Table 1. Shadowgraphs of combustion processes declared the possibility of achieving a five-point ignition scenario relatively simultaneously with this method as shown in Fig. 13. There, a two-point laser-induced cavity ignition is achieved by the open cavity in the prechamber and the conical cavity at the main chamber, and an additional three-point ignition by the ejection of hot burnt gases: one from the open cavity and two from the jet holes.

The effects of multi-point versus single-point cavity ignition on flame initiation period and combustion time were also reported and the results are summarized in Table 2 [23]. The total combustion time for case 4 was 5 ms, which is approximately seven times shorter than that of the baseline case 1 of 33 ms. Also, the flame initiation period for case 4 of 3.1 ms was about a half of that for case 1 of 5.8 ms. Note that the total combustion time of 5 ms for case 4 is comparable to that in practical spark ignition engine operation, where the flow in the combustion chamber is highly turbulent and assisted with swirl and/or tumble, although this experiment has been done with the initial quiescent environment.

Finally, Weinrotter et al. [27] investigated multi-point laser-induced spark ignition of hydrogen–air mixtures using a Q-switched Nd:YAG laser at 1064 nm with a pulse duration of approximately 5 ns. Their experiments were carried out under engine-like conditions in a high pressure, constant

volume chamber (up to 25 MPa peak pressure) at an initial temperature of 473 K and an initial pressure of up to 3 MPa. In their work, different multi-point ignition setups for hydrogen–air mixtures under high pressures were studied. The first measurement series incorporated ignition with two plasmas at each side of the combustion chamber resembling the method used by Phuoc [22]. In this regard, the laser beam was split up into two beams using a 50% beam splitter. Each of the two laser beams was focused by an uncorrected convex lens (f=70 mm) into the combustion chamber. In this way, both plasmas were produced at the same time. The distance between the two laser-induced plasmas was 184mm and the distance of each plasma to the chamber wall was 17 mm. At last, a diffractive lens (Coherent), as depicted in Fig. 14, was used to focus the laser beam to three plasmas with a mutual distance of approximately 5 mm. It had a focal length of f=62 mm and was positioned in front of the combustion chamber instead of the f=60 mm spherically corrected convex lens. The air/fuel equivalence ratio was λ=4 and the ignition energy for every focal point was 8 mJ (far above the minimum pulse energy for hydrogen–air mixtures of approximately 3.5–4 mJ which was determined for these initial parameters), corresponding to a total laser pulse energy of 16 and 24 mJ for two point and three point laser-induced spark ignition, respectively.

The significantly faster combustion of the two point ignition can be observed in Fig. 15(a). In this case, the time until peak pressure is shortened by approximately 50% and the peak pressure is 7% higher. The difference in the pressure histories of the single point ignitions through either the right or the left window of the combustion chamber can be explained in the construction of the combustion chamber being not exactly symmetrical. In Fig. 15(b), different pressure histories are plotted: three with single point ignition and three with three point ignition. It can be clearly recognized that there is no significant difference in the pressure histories for the single and three point ignitions. A possible explanation for this lack of difference in the pressure histories is that the three plasmas were situated too close to one another, so they were acting like single plasma.

Pressure histories for single and three point ignitions with a 50% higher pulse energy per focal point (12 mJ) can be observed in Fig. 15(c). With this higher ignition energy, the three point ignition pressure histories are significantly slower than the single point ignitions. If the plasmas are situated very near to one another, like 5mm in these experiments, the shock waves produced by the plasmas could disrupt one another and hence increase the combustion time.

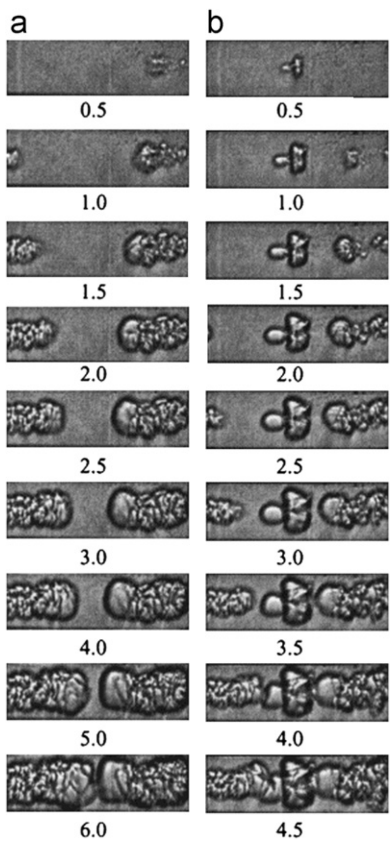

Fig. 11. Shadowgraphs for early stages of combustion processes of H_2/air mixture of ϕ=0.3 at P_i=2.0 atm; (a) two-point ignition and (b) three-point ignition (numbers indicate time [ms] after laser shot) [20].

Table 1
Description of experimental conditions [23].

	Prechamber	No. of cavities	Jet hole
Case 1	None	1	None
Case 2	Adopted	1	Simple hole
Case 3	Adopted	2	Open cavity
Case 4	Adopted	2	Open cavity+2 holes

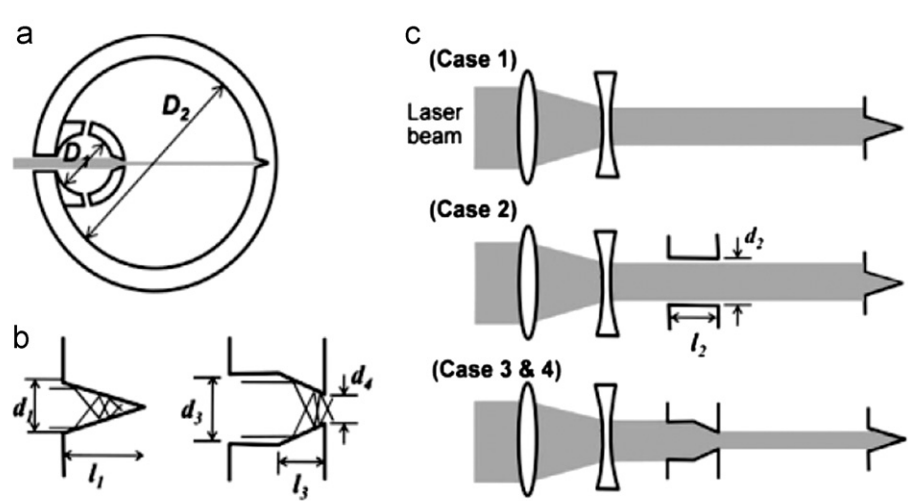

Fig. 12. Schematics of (a) combustion chamber with prechamber, cavities and jet holes, (b) principle of multiple reflection and beam focusing in conical cavity and (c) beam paths for various test cases [23].

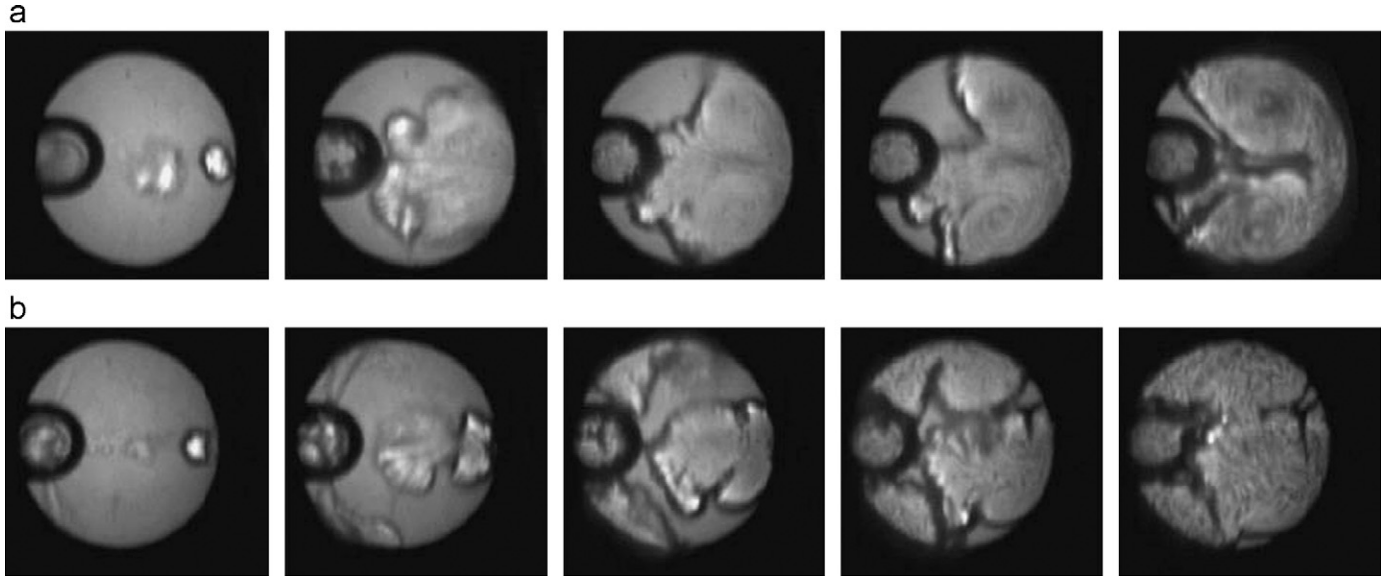

Fig. 13. Shadowgraphs of combustion processes for a stoichiometric CH_4/air mixture at P_i=3.5 atm; (a) Case 3 and (b) Case 4 [23].

Table 2
Comparison of total combustion time and flame initiation period at P_i=3.5 atm [23].

	Total combustion time (ms)	Flame initiation period (ms)
Case 1	33	5.8
Case 2	29	5.3
Case 3	12	3.4
Case 4	5	3.1

From the material reviewed concerning the developments with the innovative techniques of laser ignition, it can be concluded that significant enhancement on the combustion process, especially when burning lean mixtures, could be achieved through the use of most incident laser energy as being achieved with laser-induced cavity ignition or through simultaneous initiation of combustion at multiple locations or through increasing the turbulence level associated with ignition. The importance of these proposed techniques for laser-induced multipoint ignition is that they combine all these effects using a single pulse laser.

6. Engine studies using laser-induced ignition

To date, and according to this author's knowledge, there have been only three comprehensive reviews on laser ignition research, which were written by Ronney [25], Bradley et al. [57] and Phuoc [26]. These review papers and other associated researches have mainly investigated the fundamentals of laser ignition. However, there has been little information concerning experimental research carried out that can directly address the previously mentioned potential benefits of laser ignition as applied to automotive engines and associated control.

Internal combustion engine operation utilizing laser ignition has been the subject of a number of research efforts over the past 30 years. Yet, the practical implementation of this laser application has still to be fully realized in a commercial automotive application. Published research indicates the use of varying laser systems and delivery methods, multiple fuels, and overall improvement of engine operation and emissions production [2].

6.1. Open beam paths

One of the earliest applications of the laser ignition techniques in a gasoline engine was demonstrated by Dale et al. [28] in which they ran an ASTM-CFR single cylinder engine using a pulsed repetitive CO_2 laser operating at 10.6 μm with a pulse width of 300 ns and a pulse energy of approximately 1 J as the ignition system, and compared it with ignition obtained using a conventional electric spark. This laser provided a peak power of approximately 3.3 MW which readily ignited the test fuels; regular grade leaded and unleaded gasoline. A zinc solenoid window, with external focusing optics, mounted to the existing 18 mm spark plug hole of the engine permitted the laser beam to be focused inside the engine. They reported that the laser ignition was able to ignite a leaner mixture and that the pressure rise time was shorter compared to an electric ignition unit. However, the smaller pressure rise time led to a higher emission of NO_x. Ignition failure never occurred with the laser system; only partial burning due to slow flame travel limited the lean limit of operation of this engine with laser ignition system. Additionally, they found that the CO and HC emissions were comparable for the two ignition systems. Fig. 16 shows a sample of their reported results [28].

An investigation by Smith [69] focused on studying the effect of ignition location in a high swirl research engine which used a quartz disk as the cylinder head. A frequency doubled flash lamp pumped Nd:YAG laser operating at 532 nm with a pulse width of 10 ns and pulse energies in the range of 30–100 mJ was employed. This laser output produced peak powers in the range of 3–10 MW which ignited a lean, ϕ=0.8, mixture of air and propane. It was found that using a central point ignition location produced the most rapid pressure rise in the cylinder as compared to single point ignitions at other locations. This would imply that a central spark location has a beneficial effect on flame area, which gives a faster mass burning rate.

Bihari et al. [70], performed ignition tests in a natural gas fueled Bombardier BSCRE-04 single cylinder research engine (228.6 mm bore, 266.7 mm stroke, and 9.3 Compression Ratio) while comparing the performances under (i) conventional spark ignition, (ii) laser ignition where an open-path laser beam was used and (iii) laser ignition where the beam was transmitted using an optical fiber. In this work, a frequency doubled flashlamp

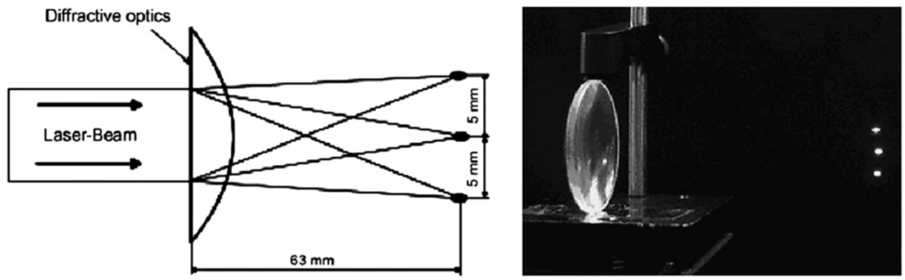

Fig. 14. Photograph and sketch of the schematic function of the diffractive lens (Coherent) producing three plasmas; total laser pulse energy 24 mJ; atmospheric pressure; focal length $f=62$ mm; distance between the three plasmas: 5 mm each [27].

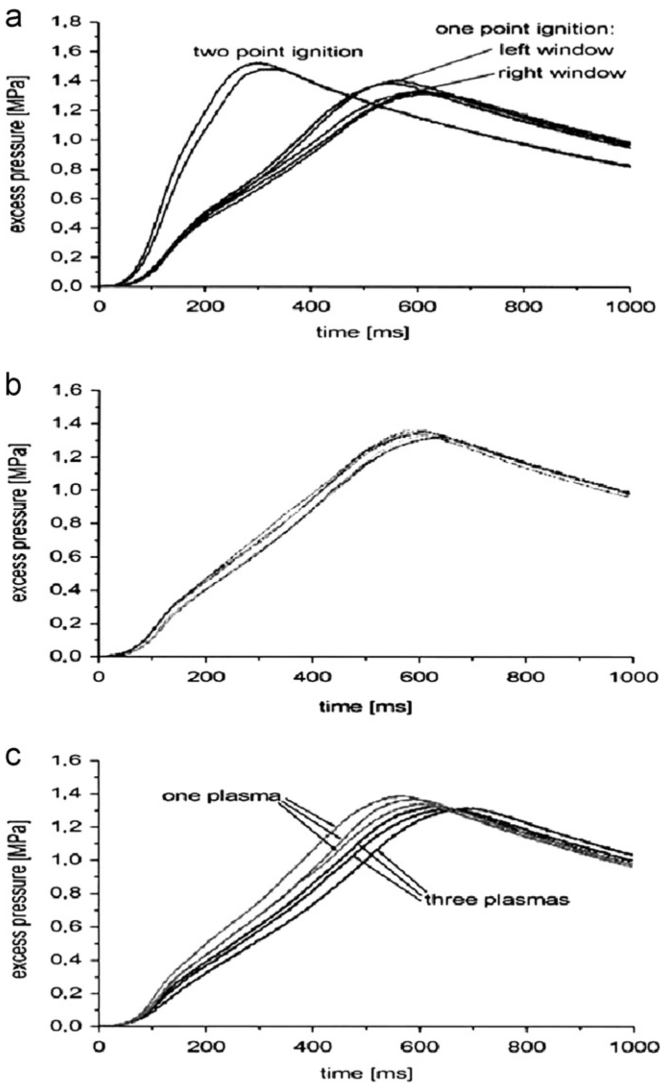

Fig. 15. Pressure history of H_2–air in the combustion chamber for single, two and three point ignition; $\lambda=4$; initial temperature = 473 K; initial pressure = 1 MPa; (a) Comparison of one- and two-point ignition ((b) and (c)) Comparison of single and three point ignition: Ignition energy per focal point was (b) 8 mJ and (c) 12 mJ [27].

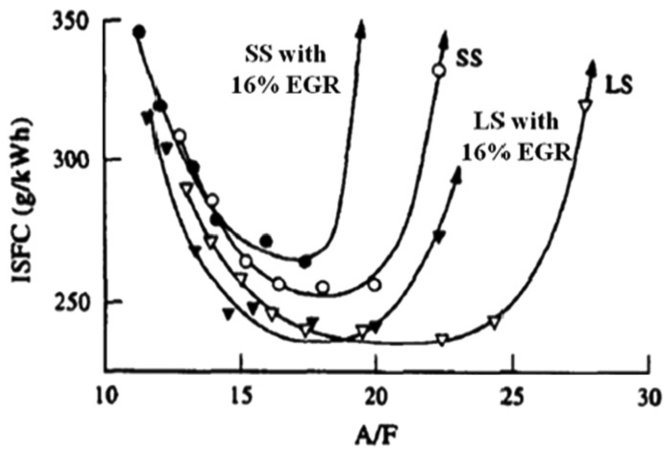

Fig. 16. Engine specific fuel consumption with standard spark (SS) and laser spark (LS) ignition systems in a gasoline engine [28].

pumped Nd:YAG laser operating at 532 nm with a pulse width of 8 ns and delivering a pulse energy up to 33.5 mJ (laser output produced a peak power of 4.1 MW) was used. The conventional spark ignition system provided approximately 125 mJ to the primary coil. After accounting for transmission and thermal losses, it was estimated that ~70 mJ of energy was transmitted to the spark. The spark plug used had 3 ground electrodes and was located at the same position as the laser plug. The engine was operated at 15 bar BMEP, or 1307 Nm of torque at 900 rpm, with both a conventional ignition system and laser ignition system. The engine ran for more than 12 h exclusively on laser ignition without significant combustion deposits formed on the lens.

Fig. 17 compares the NO_x/brake thermal efficiency (BTE) trade-off for the two ignition systems in a manner consistent when comparing lean burn technologies [70]. It was found that, as the engine ran leaner, the trend moved towards lower BSNOX. Laser ignition allowed the engine to run leaner and extend the trend. The engine, using open chamber spark ignition and operating at 90% of the misfire limit (typical of lean burn applications) could be ~32% thermally efficient and emitted 15 g/kW-h (11 g/bhp-h) of NO_x. Maintaining the same misfire margin and thermal efficiency, the engine had NO_x emissions of ~7.5 g/kW-h (5.5 g/bhp-h) when ignited by laser energy. It was primarily noticed that NO_x emissions reduce by 50% under full load conditions with up to 65% reductions noticed under part load conditions. Also, the lean ignition limit was significantly extended and laser ignition improved combustion stability under all operating conditions [70].

Researchers at the University of Liverpool in collaboration with the Ford motor and GSI Lumonics [71–74] conducted experiments in which a Q-switched Nd:YAG laser operating at 1064 nm wavelength has been used to successfully ignite and run (for extended periods) either one cylinder of a four cylinders internal combustion engine [71,72], where the remaining three cylinders were ignited using conventional electrical spark ignition (SI), or all of the four cylinders [73,74]. An optical plug was designed through which the laser beam was directed into the engine. Photographs comparing the two ignition systems are shown in Fig. 18 [74]. It is evident that the plasma produced by the laser is significantly more intense than that of the spark plug.

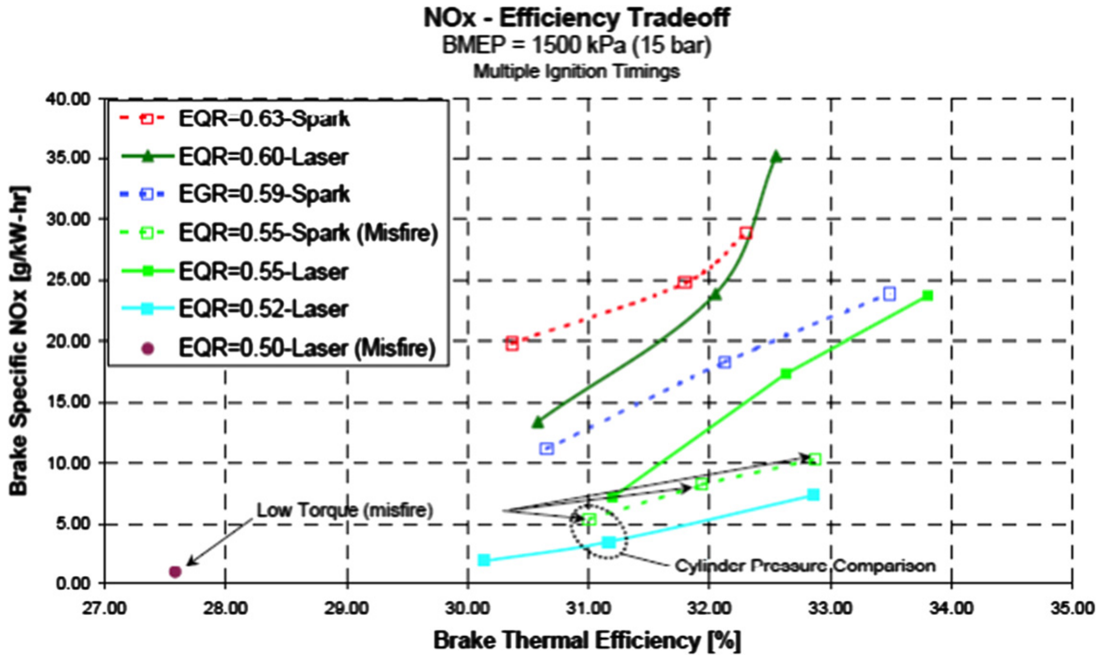

Fig. 17. NO_x—Efficiency trade-off for a natural gas fueled engine at 15 bar BMEP [70].

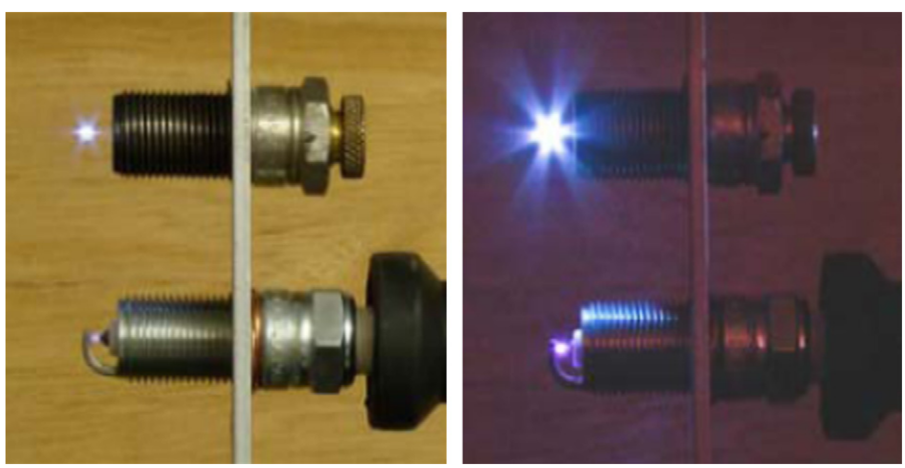

Fig. 18. Two photographs comparing a sparking optical laser plug (top) and a conventional spark plug (bottom) [74].

A normally aspirated port fuel injected 1.6L Ford Zetec engine was used for testing the two ignition systems. The authors presented their results in terms of changes in the coefficient of variation in indicated mean effective pressure (COV_{IMEP}) and the variance in the peak cylinder pressure position (Var_{PPP}), measured for each engine cylinder.

Dodd et al. [71] and Mullett et al. [72] studied the variation of several laser parameters and their effect on the engine performance; namely, beam energy, beam quality, minimum beam waist size, focal point volume and focal length. It was found that successful ignition occurred when the energy per pulse was reduced from 20 to 4 mJ and that pulse energy of 7–8 mJ proved to give combustion with no misfires and no laser damage to the optical surfaces [71]. Reducing the amount of energy required for combustion is a desirable feature that allows delivery via an optical fiber.

By optimizing the laser parameters, including minimum waist and energy per pulse, it was possible to provide COV_{IMEP} and Var_{PPP} values for laser ignition that were at least equivalent to values obtained by conventional spark ignition. Furthermore, extending the pulse length did not affect the combustion; however, it reduced the damage to the optical surfaces. From the experiments carried out by varying the focal position, shown in Fig. 19 [71], it was found that the focal position of 4 mm (and to a lesser extent 5 mm) is the most preferable as a kernel initiation distance from the cylinder wall for this particular engine geometry.

The major findings from Mullett et al. [72] were that laser ignition performed better than spark ignition in terms of combustion stability for many of the focusing lenses and cavity aperture combinations used. A sample of their result is illustrated in Fig. 20 [72]. Here, it can be seen that the ratios of COV_{IMEP} LI/COV_{IMEP} SI and Var_{PPP} LI/Var_{PPP} SI become lower with increased energy, until a point where the ratios tend to level out (any ratio values <1 indicate that the laser is operating better than the spark plug). This would indicate that greater combustion performance and stability is achieved by higher laser energies up until a threshold energy level, above which there is no significant improvement. Similar observations have been reported by Alger et al. [75] who studied laser ignition of propane. The reasons for greater combustion performance and stability with increased laser energy could

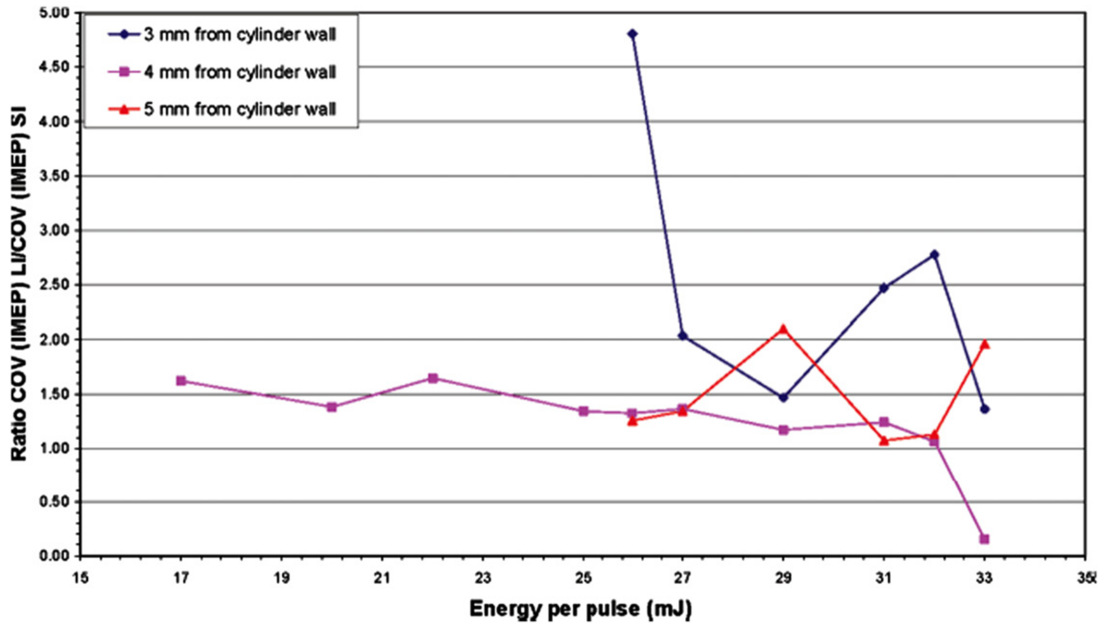

Fig. 19. Focus and pulse energy within the cylinder cumulative results from a normally aspirated port fuel injected 1.6L Ford Zetec engine [71].

be due to the plasma produced in the cylinder absorbing the extra energy. Chen et al. [76] suggest that when more laser energy is deposited into optically produced plasma, the plasma tends to expand in size instead of becoming hotter or denser. Larger plasmas produced in the cylinder can achieve faster flame kernel growth [57], which in turn reduces cyclic combustion variability [77].

Mullett et al. [73] continued their work by using laser ignition to ignite air–gasoline mixtures in all four cylinders of the test engine. Engine performance and stability using laser ignition has been compared with conventional spark ignition. Both ignition systems were triggered twice per engine cycle with one redundant spark on the exhaust stroke and the second spark on the compression stroke to ignite the air–fuel mixture. In this method the spark plugs are fired in pairs, on both the exhaust and compression strokes, where the extra spark on the exhaust stroke has no effect. However, when using lasers as the ignition system, the redundant spark may be beneficial as it could clear any combustion deposits from the previous ignition event from the optical window by the laser self-cleaning mechanism of thermal ablation. This would allow a greater amount of beam energy to be transmitted into the cylinder on the next combustion event [73].

Similar observations have been reported by Liedl et al. [78] who used laser ignition to ignite a gasoline in a direct injection engine for several 100 h without any problems. It was found that all four cylinders of the tested engine were successfully ignited from cold start without misfires using laser ignition [73]. A reduction in cycle-to-cycle variation was observed with laser ignition for a range of engine speeds (Fig. 21), loads, ignition timings and air–fuel ratios. As a result, improvements in engine performance and stability could be achieved with a laser ignition system. Furthermore, there was evidence that faster combustion durations occur with laser ignition than those for SI systems. One of the principal findings of this work was that by using a laser ignition system, it was possible to ignite leaner air–fuel mixtures more consistently, while achieving lower cyclic variation than conventional SI engines. A limitation of the tested laser ignition system was its susceptibility to engine vibrations due to the open beam optical arrangement causing misalignment after prolonged testing. One possible solution would be to use optical fiber beam delivery [79–81], as will be discussed later. Another disadvantage of the tested LI system was the use of flashlamp pumped lasers, which result in variation in the output beam properties across the operating range, limitation of beam repetition frequencies and a shorter life cycle, when compared with diode pumped laser sources, as suggested by other researchers [24,26].

Ahrens et al. [4,16] have performed open beam path tests using flash lamp pumped Nd:YAG lasers operating at 1064 nm with a pulse width of 8 ns and a pulse energy range of 10–31 mJ [16] with a peak power range of 1.25–3.8 MW. The laser beam has been introduced through a sapphire window with external optics that was adapted to both the spark plug hole and the air start port of one cylinder of a Cooper–Bessemer GMV-4TF 4-cylinder two-stroke engine to examine the effects of spark location on engine operation [16]. In their work, four different laser spark locations, as shown in Fig. 22(a), were investigated. No problems with corrosion of the sapphire combustion chamber access window were observed. However, during engine testing a problem with lens fouling (due to ablation) was encountered. They resolved the problem by using fused silica as the new lens material. A lean, $\phi=0.73$, mixture of air and domestic natural gas has been ignited [16]. It was found that laser ignition at location 1 achieved 0% misfires whereas the minimum misfire percentage for laser ignition at location 4 was 1%, as can be seen in Fig. 22(b). A small overall improvement in emissions and fuel consumption was also reported [16].

Alger et al. [75], used a flashlamp pumped Nd:YAG laser operating at 1064 nm with a pulse width of 6 ns and a pulse energy of 50 mJ. This laser output produced a peak power of 8.3 MW which ignited a lean mixture of air and propane/iso-butane. A one inch thick fused silica window was used as a pressure barrier and optical access in combination with external optics. The engine used in this study was a modified Tecumseh L-Head single cylinder engine with a displacement of 0.455 L. The aim of their work was to determine the lean limit of the engine using laser ignition. In addition, the effect of varying the energy density of the ignition kernel was investigated by changing the focal volume and by varying laser energy. The results indicated that for a fixed focal volume, there was a threshold beyond which increasing the energy density [kJ/m^3] yields little or no benefit which is similar to the results obtained by Mullett et al. [72]. In contrast, increasing the energy density by reducing the focal volume size decreases lean performance once the focal volume is

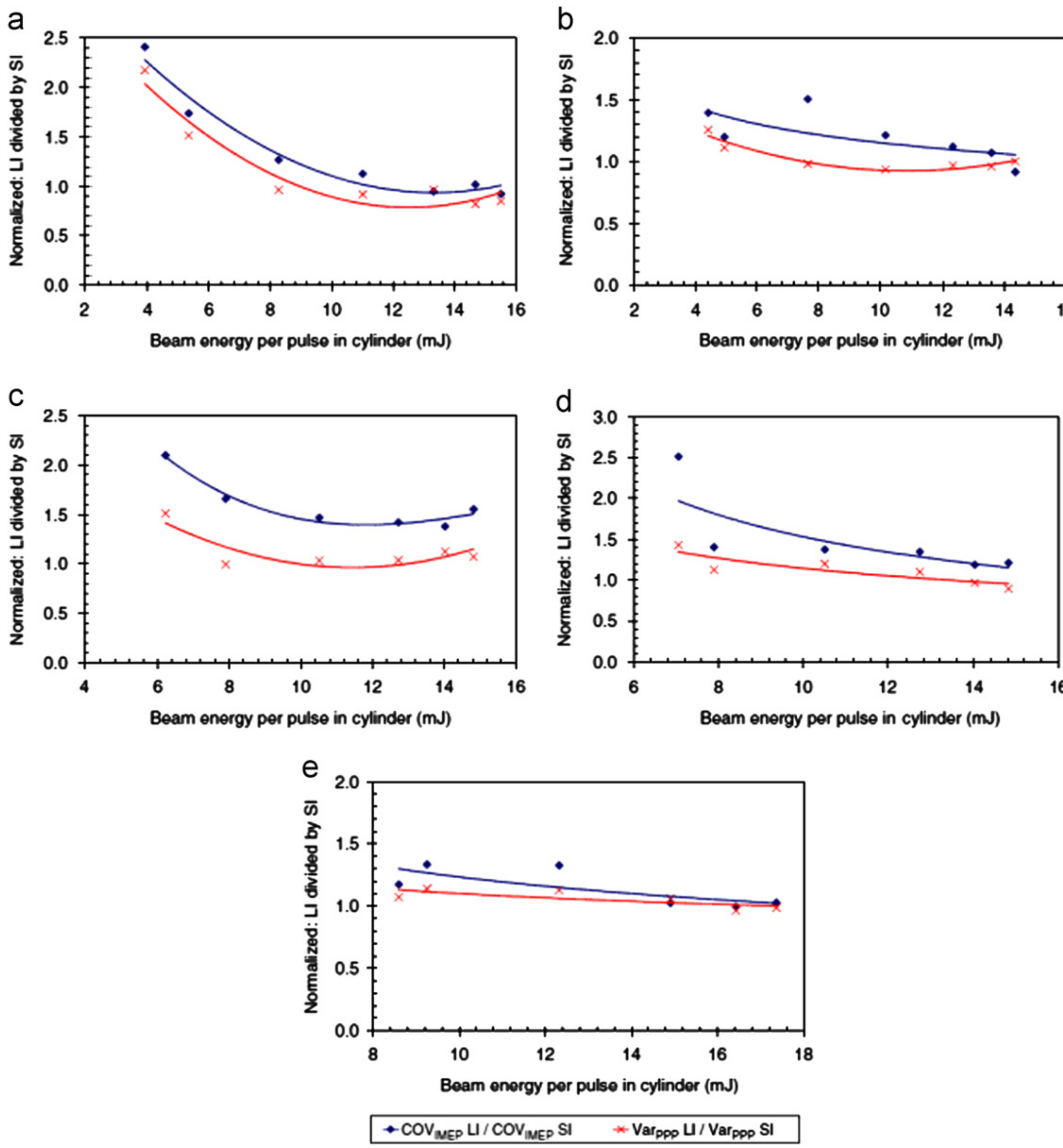

Fig. 20. Effects of increasing laser energy in cylinder 1 on the ratios of COV_{IMEP} of LI/COV_{IMEP} of SI and Var_{PPP} of LI/Var_{PPP} of SI, for a 1.3 mm laser cavity aperture diameter and lens FLs of: (a) 15 mm, (b) 18 mm, (c) 24 mm, (d) 30 mm and (e) 36 mm [72].

reduced past a certain point. The effect of ignition location relative to different surfaces in the engine was also investigated. The results showed a slight bias in favor of igniting closer to a surface with low thermal conductivity. Overall, laser ignition system was capable of igniting mixtures with equivalence ratios much lower than the typical values in an engine—as low as $\phi = 0.45$ for propane while maintaining acceptable combustion stability [75].

Weinrotter et al. [21,27,81–84] investigated the combustion characteristics of laser ignition either under engine-like conditions in a high pressure, constant volume chamber [21,27,81–84] or with a real engine [83,84]. Ignition experiments with methane–air [83], methane–hydrogen–air [27] and hydrogen–air [81,82] mixtures for different equivalence ratios and pressures ranging from 0.1 to 4 MPa using a Q-switched Nd:YAG laser operating at 1064 nm with a pulse duration of approximately 5 ns have been performed. The lean-side ignition limit of methane–air mixtures was found to be $\lambda = 2.2$. As a comparison, the limit for conventional spark plug ignition of commercial natural gas engines was at $\lambda = 1.8$ [83]. Furthermore, the necessary pulse energy for mixtures up to $\lambda = 2.2$ was only approximately 4 to 6 mJ, as can be seen from Fig. 23, which could be easily achieved by a compact diode-pumped laser. It was also found that, with higher initial pressures, the minimum incident laser energy for plasma formation was decreasing in contrast to the conventional spark plug where the energy for an ignition spark with increasing initial pressure was increasing to an upper limit [81]. In addition, it was reported that the rate of pressure rise inside the combustion chamber was higher when the mixture was ignited by laser plasma compared to spark plug ignition [82].

The real engine experiments were done using a diode pumped actively Q-switched Nd:YAG laser operating at 1064 nm with a pulse width of 5 ns and pulse energies varying from 4 to 30 mJ [83,84]. This laser output produced peak power levels in the range of 0.8–6.0 MW which were found to adequately ignite a lean mixture of air and domestic natural gas [84]. One study focused the open beam laser energy into the cylinder by a 200 mm focusing lens through a sapphire window of 5 mm thickness [83]. This study used one cylinder of a 1 MW reciprocating engine using domestic natural gas with a BMEP of 18 bar [83]. The engine

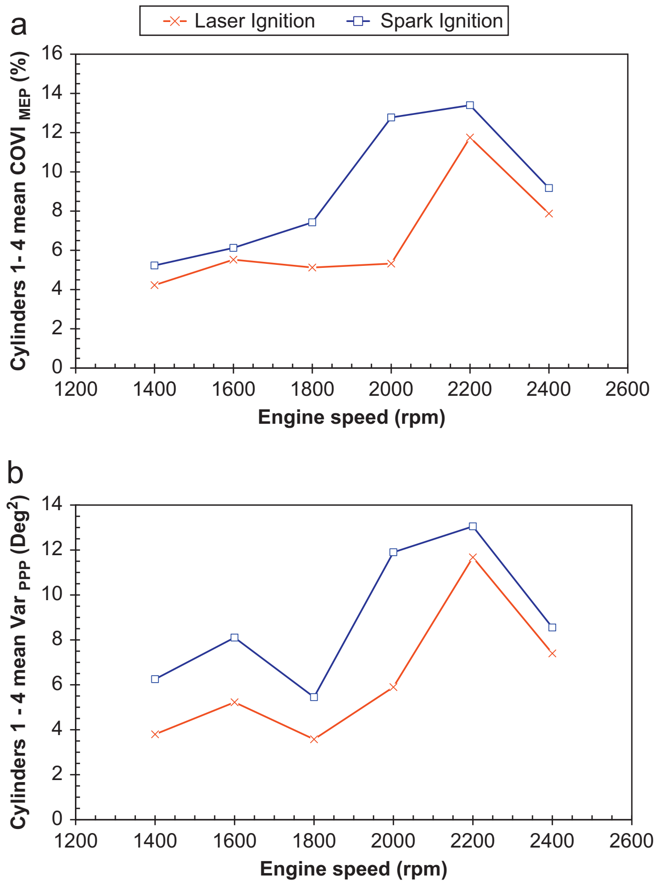

Fig. 21. Effect of engine speed on the mean (a) COV_{IMEP} and (b) Var_{PPP} for all four cylinders operating with a gasoline air mixture at λ=1.3, MBT and 58 N m torque [73].

worked successfully at λ=1.8 for a first test period of 100 h without any interruption due to window fouling and other disturbances. Lowest values for NO_x emission were achieved at λ=2.05. A subsequent study used a miniaturized diode pumped laser that was directly connected to the engine [84]. The subsequent study found that, with a very high beam quality and an output pulse energy of 1.5 mJ (the output pulse width was not reported), sufficient ignition of the fuel/air mixture was possible without any problems [84].

All published results on laser ignition of automotive (gasoline) and stationary natural gas engines have been done with open chamber plugs, i.e., the laser beams were focused inside the main combustion chamber to form a single combustion initiating spark. On the other hand, experiments have also shown increases in fuel efficiency and reductions in emissions through the use of indirect (prechamber) electric spark ignition [85,86]. However, the choice of the associated ignition approach, i.e., whether a fueled prechamber plug (in which a prechamber is equipped with a separate fuel supply system), non-fueled prechamber plug (where the fuel and air mixture is fed into the prechamber through the jet holes during the compression stroke), or just conventional open chamber ignition is engine specific. For example, the choice of the ignition approach depends on various factors such as in-cylinder fluid mechanics, engine heat transfer, ignition location, in-cylinder mixing etc. which are optimized to increase engine efficiency and lower emissions.

In this regard, Joshi et al. [87] conducted tests on a Caterpillar G3516C stationary natural gas fueled engine with three types of ignition approaches: (i) non-fueled electric prechamber plug with electrodes at the base of the prechamber (i.e., conventional ignition), (ii) non-fueled laser prechamber plug with laser spark in

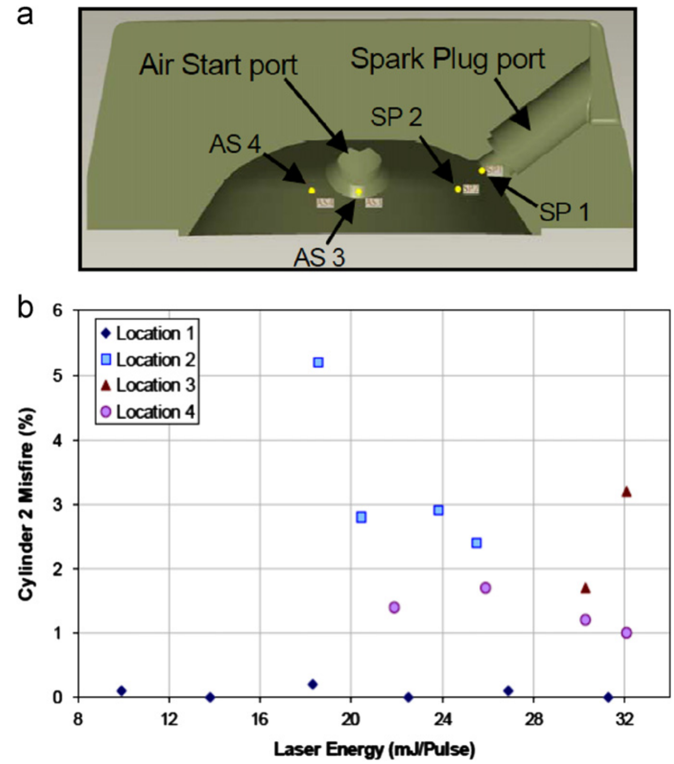

Fig. 22. (a) Four engine-test laser ignition spark locations and (b) Percent misfire for a natural gas/air mixture of ϕ=0.73 at different ignition locations for different delivered energies [16].

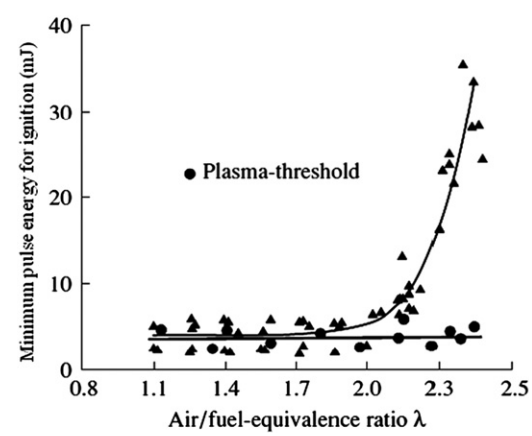

Fig. 23. Minimum pulse energy needed for ignition vs. air/fuel-equivalence ratio λ; methane–air mixtures, T=200 °C, fill pressure 30 bar [83].

the middle of the prechamber, and (iii) open chamber plug with laser spark in the main chamber. In the second configuration, a stock non-fueled prechamber plug was modified to incorporate a sapphire window and a focusing lens to form a laser prechamber plug. A 1064 nm Q-switched Nd:YAG laser was used to create laser sparks. For these tests, a single cylinder of the engine was retrofitted with the laser plug while the remaining cylinders were run with conventional electric ignition system at baseline ignition timing of 24 degree before top dead center (BTDC). It was found that the performance of the electric prechamber plug and laser prechamber plug were comparable, although small differences such as a lower degree of combustion variability with the electric prechamber were observed. The open chamber plug exhibited poorer variability in engine performance [87].

The continued development of increasingly compact and efficient laser sources and new associated laser beam delivery techniques have provided the basis for significant steps forward in research towards practical proof-of-concept demonstration of laser-induced ignition in engines for automotive vehicles [71].

6.2. Optical fiber delivery

In all of the material reviewed in the previous sections, laser spark ignition has been created adopting conventional beam delivery (open beam paths) systems which utilized lenses and mirrors to focus laser beam in order to create the gas breakdown. Such beam delivery systems are not considered practical for commercial implementation owing to safety, maintenance, thermal, and vibrational issues which can cause misalignment problems. Thus, delivery of the laser radiation through a flexible optical fiber system is highly desirable and can be considered as a key challenge for practical laser ignition systems.

The essential problem is the need to deliver relatively high-power pulses with sufficient beam quality to refocus the light to the intensity required for gas breakdown. A conventional solid core silica fiber has been investigated but without success in forming optical sparks in air at atmospheric pressure [79,88]. For nanosecond pulses in atmospheric pressure air, the reported intensity thresholds for sparking are in the range of $\sim 10^2$–10^3 GW/cm^2 [54,79]. For larger in-cylinder pressures, the threshold reduces but is of the same order.

In this contribution, Yalin et al. [89–91] have shown the possibility of using coated hollow fibers for spark delivery and have demonstrated laser ignition and operation of a single engine cylinder using hollow fiber delivery. The work represented the first demonstration of fiber coupled laser ignition (using a remote laser source) of a natural gas engine. A flash lamp pumped Nd:YAG laser operating at 1064 nm with a pulse width of 8 ns and a pulse energy of 47 mJ was used as the energy source and a coated hollow fiber, as schematically shown in Fig. 24, was used for beam energy delivery. The system was implemented on a single cylinder of an inline 6-cylinder Waukesha VGF 18 turbo-charged natural gas engine. The tests showed that the hollow fiber delivery system met the goal of providing a robust and successful means of engine ignition. Engine data showed that the fiber coupled system yielded 100% reliability in ignition and reduced combustion durations compared to conventionally ignited cylinders [90].

A potential advantage of the hollow fiber spark delivery approach was the ability to use a single laser source multiplexed (via multiple fibers) to a series of engine cylinders. In this regard, Yalin et al. [90,91] in addition to presenting the design and testing of the fiber delivered laser ignition system, they presented initial bench-top testing of a multiplexer to ignite multiple cylinders using a single laser source, and integrated optical diagnostic approaches to monitor the spark ignition and combustion performance [91]. This approach is called "step and hold" and is illustrated in Fig. 25. In this design, a mirror is stepped from one position to another and stopped, the laser fires, then the mirror is stepped to the next position. Each mirror position (and firing of the laser) causes the beam to enter a different fiber which

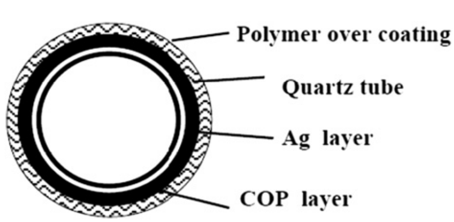

Fig. 24. Cross-sectional view of the hollow core coated fiber [90].

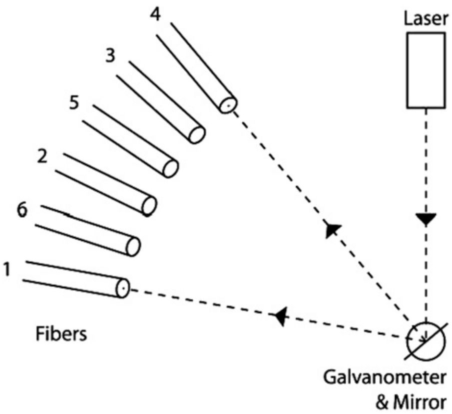

Fig. 25. "Step and hold" approach employing a mirror attached to a galvanometer. Numbers represent the order in which the fibers are fired. The interleaved design reduces the maximum step size [91].

relays the beam to a corresponding engine cylinder. Bench-top testing showed that the multiplexer can be positioned with the required accuracy and precision for launching into fiber optics, and can be switched at the relatively high switching rates needed to operate modern natural gas engines. Another test employed the multiplexer to alternately launch laser pulses into a pair of hollow fibers in a way that allows spark creation downstream of the fibers [91].

Bihari et al. [70], performed a laser ignition test similar to that reported by the same authors [70] with an open-path laser beam, which has been discussed earlier, where the laser energy was coupled to a hollow core optical fiber before being delivered to the engine for ignition. Preliminary observations of data with fiber coupled system showed results similar to those obtained in the case of open path laser ignition with the same engine [70].

Various types of optical fibers have been investigated and compared for delivering high power laser beams to an optical plug for the application of laser-induced ignition of an automotive internal combustion engine [79,92,93]. Stakhiv et al. [79] tested a number of optical fibers: step index fibers with diameters from 100 to 1000 μm, hollow-core dielectric capillaries, hollow glass fibers with cyclic olefin polymer-coated silver, and hollow-core photonic crystal fibers. A commercial 50 mJ per pulse Q-switched Nd:YAG laser emitting at 1064 nm with a pulse duration of 5 ns was also used. They reported that only hollow-core photonic crystal fibers found to be the most prospective type of advanced hollow fibers. They can offer new solutions to the problem of transportation of high-power laser pulses and could be candidates for practical use [79].

Joshi et al. [92] examined three types of optical fiber: coated hollow core fibers, fiber lasers, and photonic crystal fibers (PCFs). It was found that coated hollow core fibers (using 2 m long as a reasonable length for practical laser ignition systems on multi-cylinder engines) allows reliable (98%) spark formation with transmission of pulses of approximately 35 mJ. Owing to the decrease in breakdown threshold with pressure, such a configuration was expected to provide 100% reliability at engine pressure conditions. The transmitted pulse energies for fiber laser and PCFs were found to be far below the ignition energy needed to ignite lean mixtures in gas engines [92].

Mullett et al. [93] examined three main types of optical fiber: multi-mode step index silica, sapphire and photonic crystal. The fibers had various core sizes ranging from 35 to 600 μm and numerical apertures between 0.046 and 0.64. A Q-switched Nd:YAG laser operating at the fundamental wavelength 1064 nm with a pulse length of 15 ns was used for the testing. Fiber output beam properties, including beam mode quality, output divergence,

transmission losses, beam energy thresholds and effects of engine vibration were investigated. These fiber beam properties were compared with known beam parameters for laser ignition to assess the suitability of such fibers for a laser ignition system [93].

Fiber output beam divergence was found to decrease by reducing the beam input angle launched into the fibers, and therefore higher beam qualities could be obtained, meaning that the beam could be focused down to smaller spot sizes. However, in reducing the fiber beam input angle, the fibers became more susceptible to bending and engine vibration in terms of increased output divergence, reduced transmission and poorer beam mode quality. It was found that the fiber output beam intensity profile changed from a typical multi-mode profile to a spiral pattern as illustrated in Fig. 26, which shows the output beam profiles from a 400 μm core step index silica fiber at various output distances with and without engine vibration. This spiral mode pattern shown in Fig. 25 is undesirable for a fiber-delivered laser ignition system, as the fiber output beam quality is compromised. The sapphire fibers were shown to be the least affected by fiber bends and engine vibration. These bending and vibration effects on the fiber highlighted the need for a fiber damping mechanism in the fiber-delivered laser ignition system [93].

Of all the fibers tested, the 400 and 600 μm core diameter silica step index fibers were shown to be the most suitable for single-fiber-beam-delivered laser ignition, and were found to produce combustion in the online testing, despite a relatively large percentage of misfires [93]. It was found that the 600 μm core fiber laser ignition tests produced a higher percentage of combustion events at around 35% average, compared with the 400 μm core fiber laser ignition tests which produced only approximately 8% average combustion. It may be logical to think that a fiber core size larger than 600 μm may give a higher percentage of combustion. However, it was found that the 600 μm fiber output beam divergence, when subjected to engine vibration, reached the diameter limitation inside the optical plug. Therefore, a beam from any larger core fiber would impinge on the inner walls of the optical plug, causing large transmission losses [93].

Finally, in a more recent study by Hurand et al. [94], the output beam quality and mode coupling in various step-index fibers with core diameters of 100–400 μm and length of 2 m have been investigated for different clad dimensions, numerical apertures, and wavelengths. Fig. 27 shows output beam profiles for 200 μm core fibers with clad diameter of 330 and 745 μm. The profiles are measured after the collimating lens downstream of the fibers. The difference in the beams was striking, with a multimode structure and significant speckle (resulting from interfering modes) visible for the smaller clad and light predominantly in a single peak for the largest clad. Similarly, Fig. 28 shows the output beam profiles for 100 μm core fibers with 140 and 660 μm claddings. Again, it was found that the larger clad dimensions provided much higher beam quality, close to single mode ($M^2=1.6$). The main finding of their study was that the use of large clad solid-core fibers to deliver high-power pulses that can be focused to produce sparks is the preferred way to be adopted that can benefit laser ignition applications.

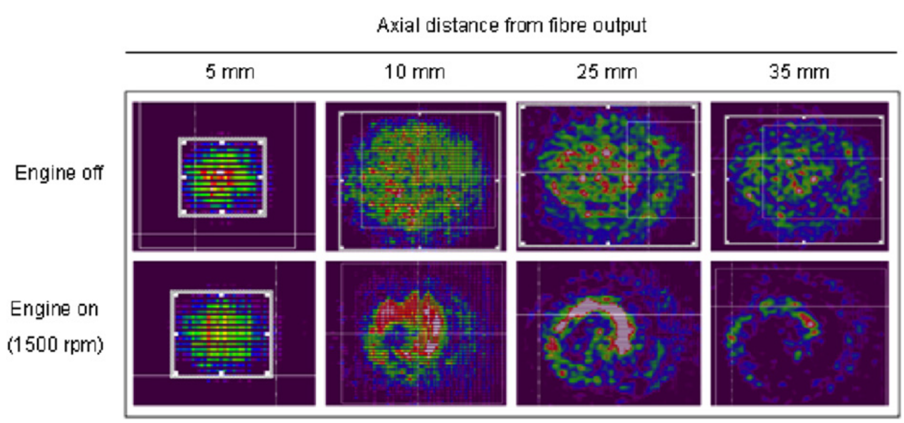

Fig. 26. Cross-sectional beam intensity profiles at various distances from a 400 μm core step index silica optical fiber output, with and without engine vibration [93].

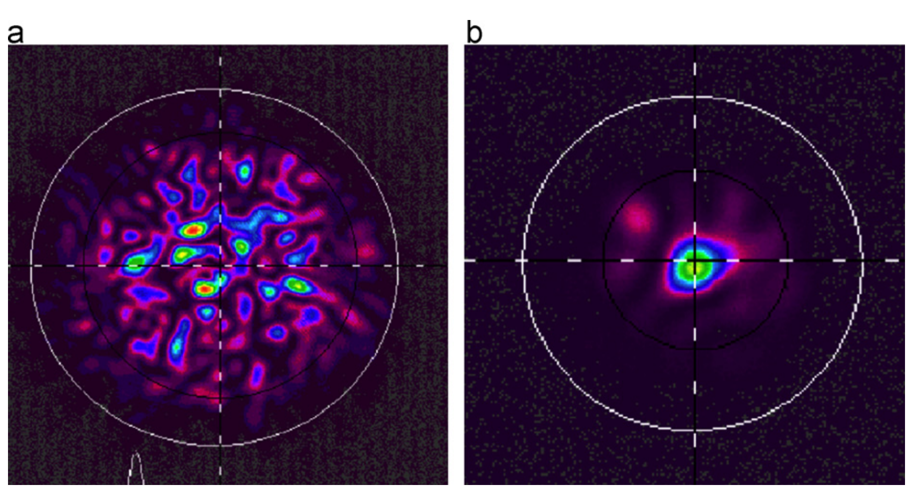

Fig. 27. Output beam profiles for (a) 200/330 fiber ($M^2=11$) and (b) 200/745 fiber ($M^2=2.8$) [94].

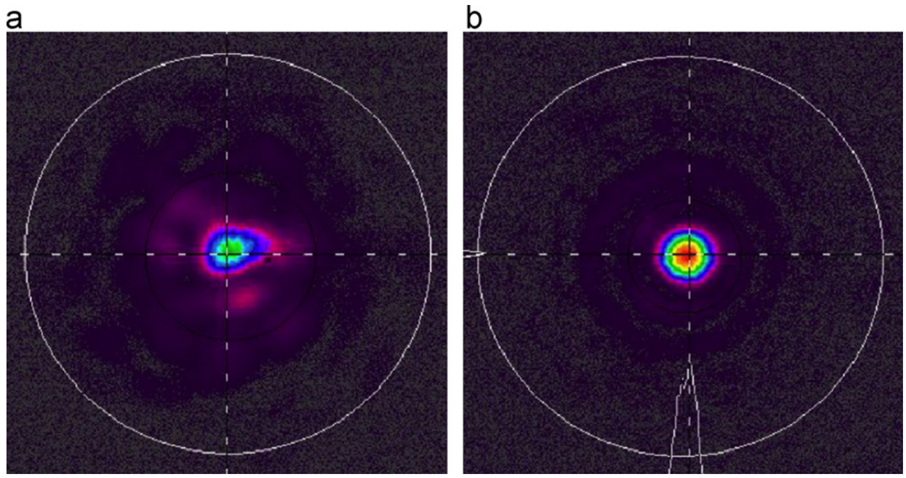

Fig. 28. Output beam profiles for (a) 100/140 fiber ($M^2=3.8$) and (b) 100/660 fiber ($M^2=1.6$) [94].

6.3. Compact laser sources

Although laser ignition shows promise as a durable high-energy ignition system for future high efficiency internal combustion engines, it has suffered from issues such as large size, heavy weight, high cost, and low efficiency. The laser cannot be attached to the engines and it has to be located far from the engines with the laser beam being delivered to the engine via a conventional optical system or a fiber optic cable system [26,70,79,89–94]. Thus, a compact, light-weight laser producing sub-nanosecond with extremely high intensity pulses is required. The laser, therefore, serves as the spark plug and it can be attached to the engine directly producing the energy for the ignition process. In this case, the use of conventional or fiber optics beam delivery systems are no longer required [26]. The development of a miniaturized low cost laser ignition system can bring the laser ignition technology from the laboratory to industrial settings and, hence, would enable advancement in the development and commercialization of higher efficiency lower emission engines.

Regarding these issues, researchers at the National Energy Technology Laboratory (NETL) used a lab scale flash lamp pumped actively Q-switched Nd:YAG laser operating at 1064 nm with a pulse width of 5 ns and a pulse energy of 50 mJ [5–8,95]. This laser output produced a peak power of approximately 10 MW which ignited a lean mixture, $\phi=0.513$, of air and domestic natural gas at a BMEP of 12 bar [6,7]. The laser was focused into the combustion chamber by a sapphire window lens that was adapted to the existing 14 mm spark plug hole of a Ricardo Proteus single cylinder engine with a displacement of 1.99 L [5–8,95]. These works have been focused on the development of experimental data to support laser ignition of lean natural gas mixtures as a viable method of improving efficiency, reducing emissions, and extending the lean limit of operation. It was found that the engine ran smoother and at leaner mixtures with laser ignition when compared to electrical spark ignition [5–8,95].

More recent engine studies were performed to verify design parameters for a miniaturized diode side pumped passively Q-switched laser developed at NETL [2,96,97]. The goal of these studies was to show that the test laser performed identically to the commercially available flash lamp pumped actively Q-switched laser used in previous laser ignition testing [5–8,95]. It has been reported that both lasers produced very similar poor combustion processes, as clearly shown in Fig. 29, which produced high levels of CO and unburned hydrocarbons due to the shortening of the focal length of the on-engine optical setup.

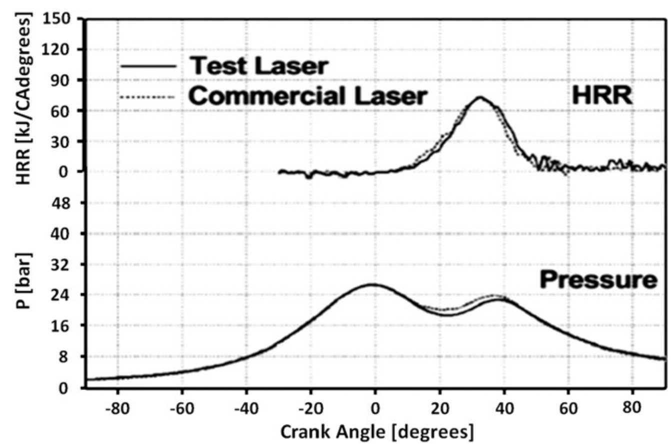

Fig. 29. Comparison of pressure and heat release rate waveforms for a natural gas/air mixture at $\phi=0.8$ [2,97].

The test laser design has been suffered from a number of curable issues including heat and vibration sensitivity, and repetition rate limitations [2,97].

The knowledge gained from the side pumped laser design was being used to develop an end pumped laser that was smaller, more powerful, cost effective, durable and safe laser spark plug ignition system which can be installed or retrofitted to any natural gas fueled engine currently using electrical spark plug ignition [2,97]. The fiber optic coupled end pumped laser spark-plug was a significant advance toward producing such a commercial laser spark plug system. The fiber optic distribution of pumping energy to a number of laser spark plugs will allow for the centralization and sharing of expensive diode laser pumps away from the heat and vibration of the engine [98].

In this regard, an extension of the side pumped laser work [2,96,97] has been performed to develop an end pumped laser system with greatly improved operational parameters [98]. The newly developed end pumped laser was packaged in such a manner that it was relatively insensitive to heat and vibration which allowed it to be directly attached to the engine unlike the previous side pumped laser design.

The design parameters and operational techniques of the miniaturized end pumped laser system were based on earlier studies of a prototype side pumped passively Q-switched laser spark plug [2,96,97]. The test laser output pulse energy was approximately 8 mJ, with a pulse width of 2.5 ns, and an M^2 value

of 5.5 which produced a focal intensity of approximately 225 GW/cm^2 [98]. The end pumped laser spark plug was mounted directly to an engine, shown in Fig. 30, running at 1800 rpm. It should be noted that previous side pumped laser spark plug engine work was kept under 600 rpm with the laser being mounted on an isolated bench to reduce the effects of temperature and vibration. It was found that the engine performance with tested laser ignition was similar to that with spark ignition with the addition of smoother operation and an extended lean limit [98].

Recently, a passively Q-switched solid-state laser, especially a Nd:YAG/Cr^{4+}:YAG laser, end-pumped by a fiber-coupled laser diode has been proposed by Kofler et al. [99] as a promising ignition laser for engines. It has a simple structure in which only two functional optical elements and no external power for optical switching is necessary and hence the dimension of the laser head could be reduced. In addition, a short pulse operation with less than 1.5 ns and pulse energies of over 6 mJ, were easily obtained by reduction of the cavity length to a value less than 10 mm. Here, the beam quality was also good due to the soft aperture effect of the Cr:YAG saturable absorber. The pump geometry was found to be a very sensitive parameter and for obtaining best performance, the pump hast to be perfectly adjusted to the given laser setup. Another problem was the pump duration because it was found to strongly affect the stability of the laser operation. At certain pump duration, it was found that the pulse energy did not increase any more, as can be seen from Fig. 31 and the laser operation became unstable due to the thermal load at too long pumping durations.

Later on, Kroupa et al. [100] developed a robust, miniaturized, diode-pumped high-energy Nd:YAG laser with passive Q-switch generating 25 mJ at 3 ns at repetition rates of up to 150 Hz. The device was designed for ignition of fuel air mixtures in internal combustion engines. The pump diodes and Peltier cooling were integrated into the laser head, giving a compact design with a small number of optical components for easy assembly. The laser was successfully operated as an optical spark plug on a test engine at high temperatures and vibration levels [100].

More recently, a high-brightness, passively Q-switched Nd:YAG/Cr:YAG micro-laser has been developed and optimized for ignition of engines by Tsunekane et al. [101,102]. The output energies of 2.7 mJ per pulse and 11.7 mJ in total (four-pulse train) were obtained at pumping duration of 500 μs with an optical-to-optical conversion efficiency of 19% where pulse duration of 600 ps and a beam quality factor, M^2, value of 1.2 were obtained. The optical power intensity at the focal point of ignition was calculated and found to be approximately 5 TW/cm^2. They confirmed that the

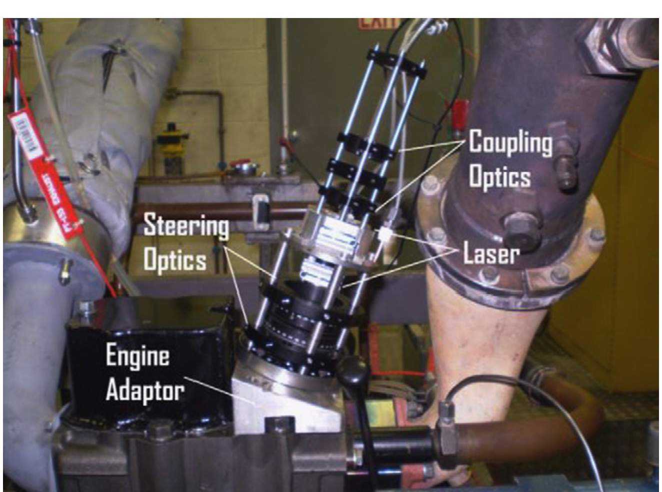

Fig. 30. Photo of laser spark plug engine setup [98].

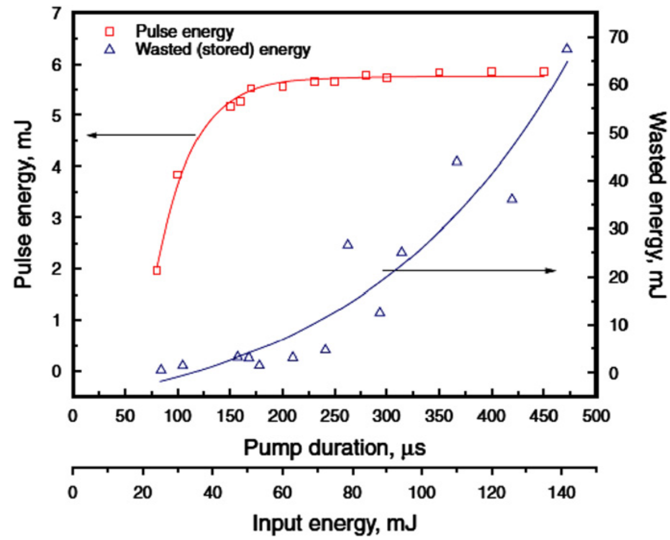

Fig. 31. Pulse energy as a function of pump duration at a pump power of 300 W [99].

output pulse energy of a passively Q-switched Nd:YAG/Cr:YAG laser did not change even though the temperature of the crystals increased to 150 °C. The enhanced combustion of a stoichiometric mixture ($A/F = 15.2$) of propane/air by the micro-laser ignition was successfully demonstrated in a constant-volume chamber with room temperature at atmospheric pressure. Ignition was successfully demonstrated by a five-pulse train in a lean mixture of $A/F = 17.2$ without any misfire, where spark plug ignition failed. Finally, ignition tests for a real automobile engine were performed. A commercial engine of 1AZ-FSE (TOYOTA Motor Corp.), which is a 2.0 L, straight-4 piston engine with a gasoline direct injection system was used. In this experiment, three of the four cylinders (from 1 to 3) were ignited by conventional spark plugs and the 4 cylinder was ignited by a laser [101]. The ignition point of a laser was set to be the same point that for a spark plug and thus this experiment was not optimized for laser ignition.

It was found that a single laser pulse with energy of 2.3 mJ, which was assumed to be the lowest energy ever reported for laser ignition of a real automobile engine, could ignite and drive the engine stably without misfire. Schlieren photographs of the early stage of ignition and subsequent combustion in a real engine for a stoichiometric mixture of gasoline and air are presented in Fig. 32. For the micro-laser ignitions, combustion processed images of three different pulse-trains, i.e., single-pulse, two-pulse and four-pulse trains, were demonstrated. The right side shows the image of a conventional spark plug ignition. Tsunekane et al. [101] confirmed that an optimally designed, high-brightness, passively Q-switched micro-laser reduced the ignition energy dramatically compared with previous ignition lasers [100] and a spark plug and the dimension of the laser head can be reduced to real spark plug size.

6.4. Ignition timing control studies

A potential application of laser stimulated ignition was as a means to actively control Homogeneous Charge Compression Ignition (HCCI) combustion timing [102–104]. The stabilizing effect of laser ignition in a reciprocating engine running in HCCI mode has been reported by Kopecek et al. [103], Weinrotter et al. [104] and Srivastava et al. [105]. Kopecek et al. [103] investigated the influence of plasma on combustion performance of HCCI engine using a laser-induced spark. It was found that, for a fuel consisting of 90% natural gas and 10% isooctane, the advance of

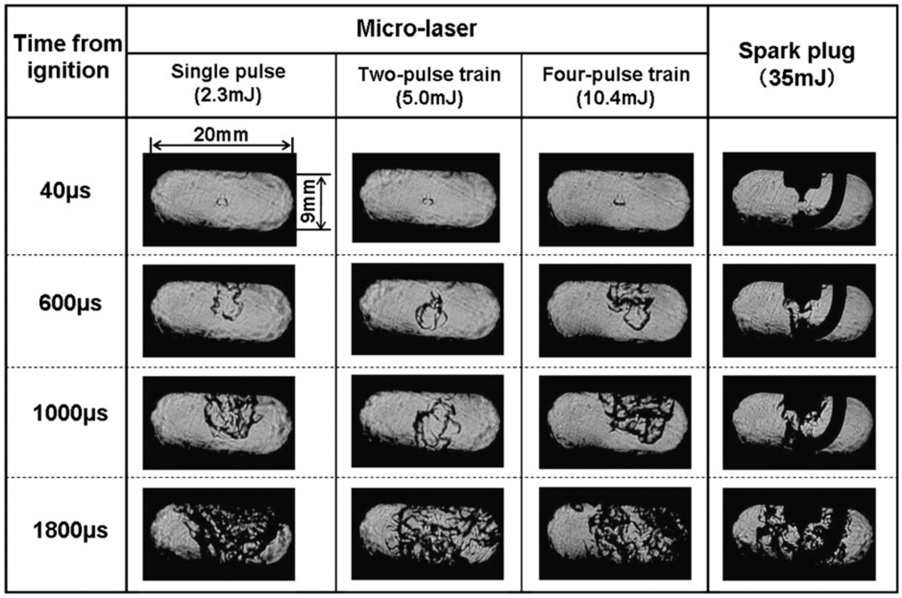

Fig. 32. Schlieren photographs of the early stage of ignitions by a micro-laser and a spark plug and the subsequent combustions in a real engine for a stoichiometric mixture of gasoline/air [101].

combustion due to the plasma was strong up to air excess ratios of λ=2.3 and to cease completely above λ=2.7. Combustion timing was advanced with increasing advance of plasma timing to a certain extent. It was found that the laser was able to sustain HCCI combustion even at much lower inlet temperatures than normally required without plasma. In addition, inlet temperature changes of more than 10 °C could not eliminate laser stimulated HCCI combustion.

A continuation of the work of Kopecek et al. [103] has been done by Weinrotter et al. [104] in which a laser-assisted HCCI and spark plug-assisted HCCI combustion was studied experimentally in a modified single cylinder truck-size Scania D12 engine equipped with a quartz liner and quartz piston crown for optical access. Their objective was to find out how and to what extent the spark, generated to influence or even trigger the onset of ignition, influences the auto-ignition process or whether primarily normal compression induced ignition remains prevailing. The beam of a Q-switched flashlamp pumped Nd:YAG laser operating at 1064 nm wavelength with a pulse width of 5 ns and a pulse energy of 25 mJ was focused into the center of the engine cylinder to generate a plasma. For comparison, a conventional spark plug located centrally in the cylinder head was alternatively used to obtain sparks at a comparable location [104].

The fuel used in these experiments consisted of a mixture of 80% isooctane and 20% *n*-heptane. It was found that, unlike in the case of methane, where the effect of laser ignition on the HCCI process was evident in the pressure and heat release curves [104], the influence of additional ignition sources on a mixture with easier autoignition properties like *n*-heptane was more subtle. The heat release curves show no significant effect on the overall performance of the engine whether unsupported HCCI or spark/laser assisted mode were investigated because the cycle-to-cycle variations have been too large. However, optical diagnostics revealed that, beginning at the ignition point, a flame structure developed and propagated in the first stage in a way similar to conventional SI engines. This indicated that when using other fuels other than *n*-heptane being less prone to autoignition like isooctane or gasoline, the effect of laser or spark plug ignition on the combustion rate or ignition timing can be expected to be more pronounced like in the case of methane [104].

A novel concept to control the start of auto-ignition by a focused-pulsed laser beam was presented by Srivastava et al. [105]. The concept was based on the fact that most HCCI engines are operated with high EGR rates in order to slow-down the fast combustion processes. A flash lamp-pumped Er,Cr:YSGG laser with pulse duration of approximately 100 μs and a fixed frequency of 20 Hz along with a variable average power of up to 6 W has been used. This laser system is normally used for dental applications. It is well known that EGR contains combustion products including moisture, which has a relative peak of the absorption coefficient at a wavelength of around 3 μm [105]. The water molecules here can absorb the incident erbium laser radiations and get heated up to expedite ignition. In their work, auto-ignition conditions were locally attained in a constant volume combustion chamber under simulated EGR conditions. It was found that the number of laser pulses required for ignition of combustible mixture decreases with increasing laser power and moisture content, as shown in Fig. 33. Taking advantage of this feature, the time when the mixture is thought to auto-ignite could be adjusted and/or controlled by the laser pulse width optimization, followed by its resonant absorption by water molecules existed in EGR [105].

Genzale et al. [106] demonstrated another potential benefit of using laser ignition: the ability to control the timing of ignition with short, nanosecond pulses, thereby optimizing the type of mixture that burns in rapidly changing, stratified fuel-air mixtures. They studied laser ignition at various timings during single and double injections at simulated gasoline engine conditions within a controlled, high-temperature, high-pressure vessel. Laser ignition was accomplished using an Nd:YAG laser beam with a pulse duration of 8 ns and a pulse energy of 10 mJ that was tightly focused at a typical location of gasoline direct injection spark plug. Ignition timing was varied during, after, and between injections of a rapid, 0.4-ms/0.35-ms dwell/0.4-ms injection schedule. Their results showed success in igniting a single injection after the end of injection, but with poor combustion efficiency due to the flame having not moved downstream to the earlier-injected charge [106]. Similar findings were also obtained when igniting after the end of a double injection. However, best results were observed when igniting between

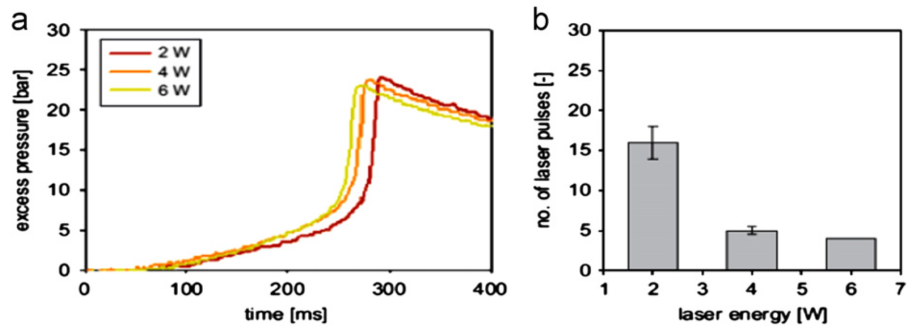

Fig. 33. (a) Pressure history of laser ignited auto-ignitions of *n*-heptane–air mixtures with 0.3 ml water ($\lambda=0.85$; initial pressure: 7.3 bar; initial temperature: 220 °C) and (b) number of laser pulses needed for resonant triggering of auto-ignition at different laser powers [105].

injections. Their results show that once the tail of the first injection has been ignited, the second injection action was to pull the flame downstream to the first-injection charge, causing high combustion efficiency. However, the timing of ignition between pulses was a critical issue [106]. If ignited too soon after the end of the first injection, ignition may fail or, even if ignition succeeds, the flame grows such that it immediately ignites the second injection, forming a fuel-rich combustion with significant soot generation. The optimal timing produced no soot formation, but still maintained high combustion efficiency. However, accomplishment of this timing required ignition timing control on the order of 0.1 ms, which is much shorter than current electric spark ignition systems that have spark durations on the order of 1.0 ms. Therefore, the benefits of this double-injection ignition strategy were only realized with the use of a short-pulse laser ignition system [106].

7. Practical significance and future needs

From the material reviewed concerning the developments with the innovative techniques of laser ignition (laser-induced cavity and multi-point ignition), it can be concluded that significant enhancement of the combustion process, especially when burning lean mixtures, could be achieved through the use of most incident laser energy as been achieved with laser-induced cavity ignition or through simultaneous initiation of combustion at multiple locations or through increasing the turbulence level associated with ignition. The importance of the proposed techniques of laser-induced multipoint ignition is that it combines all these effects with a single laser pulse.

In addition, although some of the advantages mentioned previously for laser-induced spark ignition are thereby sacrificed with laser-induced cavity ignition, the innovative technique of laser-induced multi-point ignition is mainly based on using either a cavity on one side (two point ignition) or two cavities on both sides (two and three point ignition) of the combustion chamber [19,20,23], which could be assumed as the main benefit of using laser-induced cavity ignition. However, all of these studies were of a fundamental nature and the application of these innovative techniques to real engine should be examined.

The material reviewed of laser spark ignition in engine testing has shown an extension of the lean limit of operation [2,5,6,28,70, 74,75,81–84,95–98] as well as significant reduction of NO_x emissions [7,84] and a reduction of ignition delay [6,8,16,69] but with longer burn durations [6,8,69]. Increased combustion stability [6,8,72,75,84], improved performance [6,8,28,72,75,84], reduction in cycle-to-cycle variation [74] laser spark ignition location sensitivity [4,16,71], laser spark ignition location insensitivity [28,69] and the ability for ignition timing control [103–106] were also

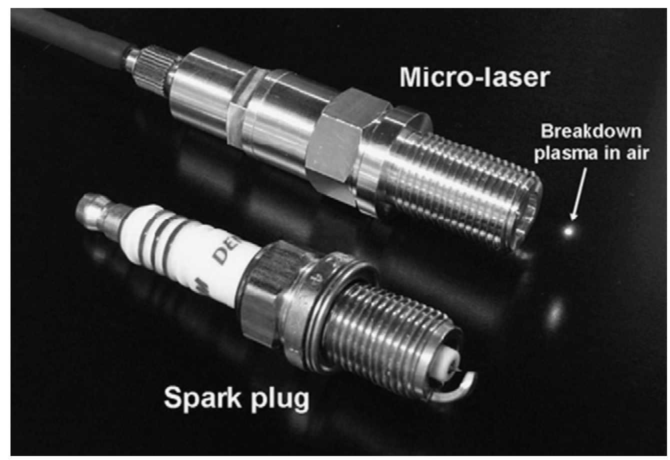

Fig. 34. Prototype spark plug size micro-laser head and a conventional spark plug [101].

reported in the literature. Furthermore, it was possible to localize the laser ignition adaptively to get optimum ignition conditions in an inhomogeneous mixture [107].

It is evident that laser ignition systems can offer a significant number of opportunities for improved combustion control, through the delivery method of the laser beam to the desired focal position(s) and through a new generation of laser sources. Further developments in engines are assumed to include adjusted designs for injection, mixture formation and laser ignition with close relations to each other to get the best extent of optimizations [107]. A number of future prospects for laser ignition have been suggested [74,101,108], which include:

7.1. *Optimized cylinder head design with variable ignition location*

The entry position of the ignition source on the cylinder head of the engine becomes far less critical with laser ignition since optical elements can be used to obtain the desired ignition location. Furthermore, the entry for the laser beam could be made considerably smaller than or at least equal to that required for a spark plug. As such, there is significant scope for future cylinder head designs to better optimize the injection location or to increase valve sizes [74]. Fig. 34 shows the first prototype micro-laser module which has the same dimensions as a spark plug [101,102]. This module includes not only pumping optics from a fiber to a solid-state material but also beam expanding and focusing optics for ignition. The laser igniter was physically able to ignite in a real engine by installing it in the same hole of the spark plug. For real operation on an engine, however, the mechanical design inside the

module should be improved to sustain the high temperatures and vibration of a real engine.

Furthermore, the position of the ignition location can be readily changed by selecting suitable optical elements allowing deeper ignition location than that with a spark plug. Detractive optical elements can also be used to focus a single laser beam to multiple locations within the combustion chamber [74]. Variable telescopes can also offer a relatively simple method of dynamically varying the ignition position within a cylinder. In addition, emerging technologies have seen the introduction of liquid lenses which can dynamically change the focus. Further development of such technologies could allow the focal position to be changed depending on the operating condition of the engine [74].

7.2. Monitoring of combustion process

Laser ignition provides a clear optical pathway into the engine cylinder, due to the self cleaning mechanism of the laser beam entering the combustion chamber [73,78]. The beam removes combustion deposits from the optical plug window, which allows the light generated during the combustion process to be monitored. This light-signature provides an opportunity to perform a real-time estimation of the combustion temperature, emission species, equivalence ratio [108] and pressure, through signal processing and pattern recognition methods. The plasma created by the focused laser beam to create the spark for combustion naturally lends itself to laser induced breakdown spectroscopy diagnostics. Alternative laser based combustion monitoring includes laser-induced fluorescence and laser-induced incandescence. All of these techniques can be used for the online real-time feedback control of combustion.

7.3. Future needs

Although the cost and packaging complexities of the laser ignition systems have dramatically reduced to an affordable level for many applications, they are still prohibitive for important and high-volume applications such as automotive engines. However, their penetration in some candidate markets, such as large stationary power plants and military applications, are imminent [109,110]. In addition, as being reported by Tauer et al. [110], the high potential for improving direct-injection Otto engines by laser ignition may later lead to its industrial implementation associated with huge numbers of units, given that the cost constraints can be solved.

The delivery of the laser beam into the combustion chamber can be realized by various approaches [24,110,111], two of them are:

- Separate ignition laser can be mounted on every cylinder head being supplied by an external pump source (laser diode), where the pump pulse is transported via a standard optical fiber;
- The laser unit and engine are separated to avoid influences such as vibrations and excessive temperatures on the ignition unit with the ignition pulses being transported via optical fibers to the combustion chamber.

In order to fully exploit the benefits of laser ignition, there are some issues that need further investigation before an optimized control scheme can be found [74]. For a realistic application to work in internal combustion engines, the laser system should be assembled in housing with similar dimensions to a spark plug [99]. Furthermore, the laser will be exposed to high thermal and mechanical stresses and, hence, the system has to be engineered in a very robust form. Therefore, the temperature and vibration influences on the laser should be further investigated. Promising results were observed in instances where YAG ceramics were used to provide the actual light sources for laser ignition due to their high uniformity, stress resistance and their suitability for mass-production [101,110]. In addition, if a composite structure of Nd:YAG/Cr:YAG is possible, then the compact and rugged, monolithic laser cavity could be made to achieve the required robustness. Reports also show that an optimally designed, high-brightness, passively Q-switched micro-laser can reduce the ignition energy dramatically compared with previous ignition lasers and spark plug mechanisms along with a reduction in laser head size to that comparable to a real spark plug size [99].

A compact, passively Q-switched Nd:YAG/Cr^{4+}:YAG giant-pulse emitting micro-laser with three-beam output has been realized by Pavel et al. [112]. This prototype laser incorporates a composite, all-ceramics Nd:YAG/Cr^{4+}:YAG monolithic medium that was pumped by independent lines. Fig. 35(a) shows a schematic of the experimental set-up used for the proposed laser. A photo of this prototype laser with the three-beam output and following breakdown in air is shown in Fig. 35(b) where the laser size is comparable to that of an electrical spark plug. Pavel et al. [112] reported that at a 5 Hz repetition rate, each line delivered laser pulses with approximately 2.4 mJ energy and 2.8 MW peak power. Increasing pump repetition rate up to 100 Hz improved the laser pulse energy by 6% and required approximately 6% increase of the pump pulse energy compared with operation at 5 Hz. Pulse timing of the laser-array beams could be controlled by changing the pump energy of each individual line. Using this kind of laser, simultaneous multi-point ignition was possible by less than 5% tuning of the individual pump line energy, which could enable studies of the performance of internal combustion engines with multi-point ignition [112].

The transportation of ignition pulses via optical fibers implicates some plain advantages. Fiber delivery increases safety, allows the laser to be located away from the high temperature

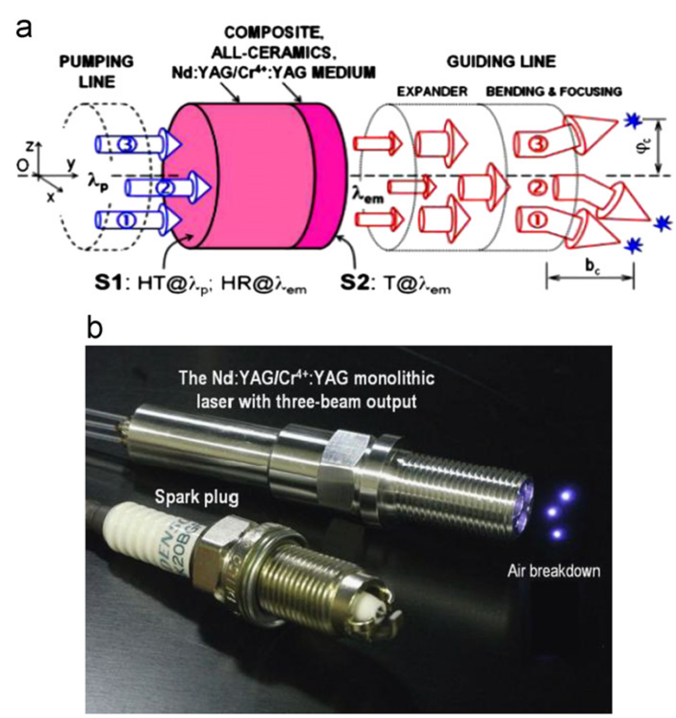

Fig. 35. (a) Schematic of a passively Q-switched, all-ceramics, composite, Nd:YAG/Cr^{4+}:YAG monolithic laser with three-beam output and (b) a photo of the prototype laser showing breakdown in air [112].

conditions near the cylinder, and, especially for multi-cylinder engines, should enable lower cost multiplexed solutions when compared to mounting a laser on each cylinder [94,110]. Furthermore, a conventional laser unit removed from the engine itself could be employed because there are almost no requirements regarding the size and robustness of the laser system [110]. However, as a matter of fact, the restrictive factor is the damage threshold of the fiber material. Such pulses may induce intensities in a small core far beyond 1.5×10^9 W/cm^2 which is the breakdown threshold of fused silica for ns-laser pulses. Furthermore, the tolerance for misalignment at launch becomes exceedingly difficult to maintain in practical systems, and diffraction and lens aberration may limit focused spot sizes, making it difficult to reduce the fiber output [94]. An enlargement of the solid fiber core area, where the beam is guided, in order to reduce the intensity is not adaptive since for fixed wavelengths higher core diameters imply multi-mode beam profiles. Therefore, it is desirable to use large core fibers to deliver high-power laser pulses with sufficient beam quality to focus the output light to the intensity required for breakdown.

The increase in beam quality with large clad can be a useful strategy and does not pose practical restrictions as long as the overall dimension being not so large as to introduce mechanical problems. Furthermore, it has been recently shown that large clad fibers can be used to deliver high-power pulses that can be focused to produce sparks in atmospheric pressure air, which was the first demonstration of this kind with step-index fibers that can benefit laser ignition applications [94].

However, there exist some concepts for the transportation of ignition laser pulses via hollow core optical fibers. The employment of photonic band gap fibers would bring some advantages like single-mode propagation. Unfortunately, it has been reported that the highest transmitted single pulse energy was approximately 0.8 mJ which is not adequate for igniting lean mixtures [113]. Further improvement of hollow fibers has to be successfully achieved before an increase in the delivered pulse energy up to a level sufficient for laser ignition can be realized.

In contrast to the ignition pulse, the pump beam can be guided via conventional optical fibers since the intensity is lower by approximately six orders of magnitude. Furthermore, the pump beam generated from diode bars generally is not of a single mode nature and therefore only multi-mode fibers are appropriate.

In addition, if fiber-delivered laser ignition is to compete with spark plugs in the future, then the lifetime of the optical fibers should last at least 10,000 miles ($\sim$500 h) of operation [93]. Therefore, the fibers must be able to withstand engine heat and vibration for prolonged hours of use. Moreover, the longevity of the optics within the optical plug (lenses and windows) should also be assured. Therefore, future studies in the field of laser ignition should investigate the long term effects of these optical elements in a harsh engine environment, as there is insufficient research in this area [93].

Also the use of the combustion chamber window is surely a crucial component for the success of laser ignition and this additionally plays an important role in cost optimization [84,110]. The diode laser, i.e., the pump diodes, have prognosticated service lives of more than 50,000 h, and therefore the combustion chamber window, i.e., the system, must also reach a service life window of at least 10,000 h to attain the objective of development. However, the physical limits of the various possible window materials presently still lie very close to the limit to be attained [84,110].

Finally, practical commercial applications of laser ignition technology require low cost high peak power lasers. The lasers must be small, rugged and able to provide stable laser beam output operation under adverse mechanical and environmental conditions. Estimated basic cost and performance requirements of a practical laser spark plug, reported by Myers et al. [114], are listed in Table 3.

Table 3
Laser spark plug cost and performance requirements [114].

Mechanical	Laser and mounting must be hardened against shock and vibration
Environmental	Laser should perform over a large temperature range
Peak power	Laser should provide megawatts raw beam output
Average power	1-laser per cylinder requires 10 Hz for 1200 rpm engine operation
Lifetime	100 million shots – good, 500 million shots – better
Cost (stationary)	Laser cost less than \$3000 each (100 Mpulse life $\sim$ break even)
Cost (automotives)	Laser cost less than \$600 each

The cost values shown are based upon the estimated operational costs of a laser spark plug of an 800 kW 16-cylinder Waukesha natural gas engine operating at 1200 rpm with 16 lasers (one for each cylinder). If the laser operates 24 h a day, 365 day a year at 10 Hz (10 cycles/s), a total of approximately 315 Mpulse per year is required. A case study of the natural gas fuel consumption cost estimation for this engine based upon \$10 per MBtu, \$65.00/h is found to be approximately \$569,000 per year [114]. Replacement of a conventional spark plug by a laser one provides an estimated 40% decrease in fuel consumption [114]; under these conditions, the fuel consumed with the laser spark plug requires \$46.00/h which can be translated into fuel cost savings of approximately \$166,000 per year. Laser replacement cost (materials only) is estimated to be \$144,000 ($16\times$ \$3000 each $\times\,3$ times per year with an estimated 100 Mpulse lifetime). This cost analysis indicates that laser spark plug lifetime is a key issue with regard to the development of an economically viable laser spark plug [114].

8. Concluding remarks

In this paper, innovative techniques of laser ignition have been reviewed and the feasibility of using such techniques for practical applications, especially internal combustion engines, has been discussed.

It can be concluded that significant enhancement to the combustion process (especially when burning lean mixtures) could be achieved through the use of most incident laser energy as being achieved with laser-induced cavity ignition or through simultaneous initiation of combustion at multiple locations or through increasing the turbulence level associated with ignition. The importance of the proposed techniques of laser-induced multipoint ignition was that it combines all these effects with one single pulse laser. However, the application of these innovative techniques should be examined in real engine environments. Other techniques such as open beam delivery systems are found to be impractical for commercial implementation owing to safety, maintenance, thermal, and vibrational issues which can cause misalignment problems.

There are two promising concepts by which the delivery of a laser beam into the combustion chamber can be realized, namely the laser mounted on the cylinder or located at a remote location [111]. Both concepts adopted optical fibers to transport either the ignition pulse or pump pulse. Thus, the development of a flexible optical fiber system is highly desirable and can be considered as a key challenge to bring laser ignition into a realistic application to internal combustion engines.

In addition, an optimally designed, high-brightness, passively Q-switched micro-laser has been confirmed to reduce the ignition energy dramatically compared with other ignition lasers and a spark plug [101]. At the same time, the dimension of the laser head can be reduced to real spark plug size. Furthermore, if a

composite structure of Nd:YAG/Cr:YAG is possible, then the compact and rugged, monolithic laser cavity could be made to achieve the system robustness [99,101].

Moreover, a need was found for the technology development of the combustion chamber window (a component crucial for the success of laser ignition) and plays an important role in cost optimization [110]. However, the physical limits of the various possible window materials presently available still lie very close to the limit to be attained [84]. Therefore, further studies leading to the development of window materials suitable for laser ignition systems are necessary.

Finally, and despite the continuous reduction in laser equipment costs, up to date there is still a lake in the availability of a commercial system that can fulfill the requirements to replace conventional spark ignition systems and it is still prohibitive to be used in important applications such as automotive engines. A possible breakthrough light come when such laser applications begin to enter candidate markets such as military and large stationary power plants applications.

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